PB83-169953

Population Risks from Disposal of High-Level Radioactive Wastes in Geologic Repositories

(U.S.) Office of Radiation Programs
Washington, DC

Dec 82

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. 520/3-80-006	2.	3. RECIPIENT'S ACCESSION NO. PB83 169953
4. TITLE AND SUBTITLE Population Risks from Disposal of High-Level Radioactive Wastes in Geologic Repositories		5. REPORT DATE 1980 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) C. Bruce Smith, W. Alexander Willimas, B.Serini, Daniel J. Egan, Jr., James Gruhlke, Cheng-Yeng Hung		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Same as box 12		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Protection Agency (Radiation Programs) 401 M Street, S.W. Washington, D.C. 20460		13. TYPE OF REPORT AND PERIOD COVERED Draft Report 14. SPONSORING AGENCY CODE 200/03
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

This technical report presents these assessments of long-term repository performance. It describes the models that the Agency developed specifically for this project, reviews the various assumptions made, and identifies the data used in these models. In general a relatively simple analytical methodology was formulated that should tend to overestimate the long-term risks from geologic repositories. Because much of this methodology is new, and because these risk assessments are a key part of our rulemaking, the Agency is publishing this as a draft report. During the public comment period on 40 CFR 191, a Subcommittee of the Agency's Science Advisory Board will conduct an independent technical review of our risk assessments (48 FR 509). All meetings of this Subcommittee will be announced in the Federal Register and will be open to the public. In addition, I encourage users of this report to submit any comments or suggestions they might have. Such comments would be most helpful if received by May 2, 1983, and they should be sent to: Central Docket Section (A-130); Environmental Protection Agency; Attn: Docket No. R-82-3; Washington, D.C. 20460.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT unlimited	19. SECURITY CLASS (*This Report*) unclassified	21. NO. OF PAGES 326
	20. SECURITY CLASS (*This page*) unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

PB83-169953

United States
Environmental Protection
Agency

Office of
Radiation Programs
Washington DC 20460

EPA-520/3-80-006
December 1982

Radiation

EPA

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Draft Report

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA 520/3-80-006

POPULATION RISKS FROM DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTES IN GEOLOGIC REPOSITORIES

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Draft Report

December 1982

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

FOREWORD

The Agency has recently published environmental standards addressing disposal of high-level radioactive wastes (40 CFR Part 191) for public review and comment (47 FR 58196). An important part of this effort is the evaluation of how effective mined geologic repositories are for isolating these wastes from the environment for many thousands of years. EPA's assessments indicate that carefully designed repositories at good sites can keep long-term risks below those that would exist if (on a generic basis) the uranium ore used to create the wastes had not been mined to begin with. Accordingly, the Agency has proposed environmental standards that would restrict projected releases from high-level waste disposal systems--for 10,000 years after disposal--to levels that should keep the risks to future generations less than the risks they would have been exposed to from the unmined ore if these wastes had not been created.

This technical report presents these assessments of long-term repository performance. It describes the models that the Agency developed specifically for this project, reviews the various assumptions made, and identifies the data used in these models. In general, a relatively simple analytical methodology was formulated that should tend to overestimate the long-term risks from geologic repositories.

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Chapter 1 - INTRODUCTION

The Environmental Protection Agency is developing--and has recently proposed for public review and comment (47 FR 58196)--generally applicable environmental standards for the management and disposal of high-level radioactive waste. An important part of this process is to evaluate how proposed disposal methods can limit the long-term dangers from these wastes. This report describes our estimates of the population risks associated with disposal of the wastes in mined geologic repositories.

There is a wide variety of potential disposal methods for high-level wastes (IRG 79). However, most of the research to date has focused on emplacement in geologic formations using conventional mining techniques. As a result, this method could be implemented more rapidly than any other, and more information is available to assess its potential environmental effects. Therefore, the analyses described in this report consider only geologic disposal. A report by the MITRE Corporation reviews other disposal methods (AL 79a).

High-level wastes may be potential environmental hazards for a long time. Accordingly, these analyses address environmental effects which may happen over many thousands of years. We consider unplanned releases which may occur from a geologic repository. Such releases are of particular concern since institutional controls may not be reliable over a long time. For example, human intrusion into the repository may not be prevented, and unplanned releases may not be cleaned up.

It is important that these analyses be summarized as descriptively as possible; therefore, estimates of potential excess cancer deaths have been associated with projected releases of radioactivity. However, the limitations of this part of the analysis must be emphasized. Population distributions, food chains, and technological capabilities will probably change dramatically over thousands of years. Unlike geologic processes, they can be realistically predicted only for short times. Accordingly, very general models of releases resulting from manmade events and models of environmental pathways, populations, and living habits have been developed (SMJ 82). Rather than attempt to predict future changes in population distributions, cancer cure rates, etc., the models use present values for these parameters.

The analyses described in this report consider only risks to populations, as opposed to risks to individuals. As a result, many simplifications were possible in the analytical models. Most importantly, total quantities of radioactivity released are of concern, rather than concentrations of radioactivity released. This assumption is reasonable since we are concerned with the total doses received by man and not the maximum dose to any individual. Because of these simplifications, individual doses cannot be determined from the information in this document. However, a companion report (GO 82) describes analyses that assess individual doses from several types of release.

We developed a generic reference model of a repository system to assess the population risks from geologic disposal. This model includes the amount of radioactive wastes, the waste form, the waste canisters, the repository design, the surrounding geologic media, the geochemical and hydrological properties of these media and environmental pathways. Various host rocks were considered, including bedded salt, domed salt, granite, basalt, and shale. This reference model was then used to calculate the consequences of releases from the repository to the environment for a wide variety of circumstances. The consequences are then placed in their proper perspective by combining them with appropriate probabilities of occurrence.

Relatively simple mathematical representations of each part of the repository system were used. However, there are several components, which can interact in many ways. Many combinations of parameters were studied to determine the effects of various assumptions. To perform this large number of computations, a computer program called REPRISK was developed. A FORTRAN listing of this program, instructions on its use, and a sample input and output are provided in Appendices E, F, and G. The mathematical equations and the parameters used to represent the various parts of the repository system are discussed in Chapters 2 through 6 of this report.

The reference repositories and waste characteristics are described in Chapter 2. Each component of the repositories is discussed, and the parameters used to describe each component are identified. Chapter 3 explains the mathematical equations used to calculate movement of radionuclides through groundwater pathways. Chapter 4 discusses the geochemical interactions of these radionuclides with the groundwater system; such interactions are a very important part of the overall analysis. Chapter 5 summarizes the mathematical equations used to describe the mechanisms, both expected and accidental, that may release radionuclides from the repository to the surrounding environment. These release calculations are based on the analyses contained in the report prepared for EPA by Arthur D. Little, Inc. (ADL 79). Chapter 6 provides an overview of the equations used to calculate the movement of released radionuclides through environmental pathways and the associated population health impacts; these models are more fully explained by Smith, et al. (SMJ 82). The combination of all of these models of various parts of the repository provides estimates of the population risks associated with generic reference repository system designs. These estimates are examined in Chapter 7, along with sensitivity studies which examine the effects of different assumptions about the various parts of the disposal system.

The objective of these analyses is to provide enough information to judge the adequacy of geologic disposal in limiting the release of the waste to the environment. The important characteristics of repository systems have been identified as variables to study their effects on the overall risks. These variables are used in relatively unsophisticated models which are intended to overestimate, rather than underestimate, the risks. Because of the generality and simplicity of this approach, these analyses cannot be used to judge the risks from a specific disposal system at a specific site. The detailed data and particular circumstances associated with that specific site must be considered. (For example, in our analyses, basalt repositories always show higher risks than granite repositories; however, a basalt repository at a specific site may have lower risks than repositories at many potential granite locations.) However, we do believe that the analyses described in this report provide reasonable upper bounds of the risks from geologic repositories--given the specific assumptions for each analysis. Accordingly, the Agency has used these analyses as an important tool in selecting the long-term containment requirements in its proposed standards for disposal of high-level wastes (EPA 82).

Chapter 2 - DISPOSAL SYSTEMS

We have represented a high level waste disposal respository as three interrelated subsystems which isolate the waste from the environment: the engineered controls, the surrounding geologic media, and the groundwater flow system. The first subsystem--the controls engineered to contain the waste--includes the waste matrix and the waste canisters. Other engineered controls that would help isolate the waste from the environment--but which are not included in these analyses--include material packed around the canisters and backfill in the repository to inhibit ground water movement.

The second subsystem is the natural structure of the geologic media. This report describes five types of geologic disposal media: bedded salt, domed salt, granite, shale, and basalt. The geologic media subsystem includes the host rock, the overlying and underlying geologic materials, the repository and the shafts and seals which penetrate the host rock. The original properties of the host rock media are very important; however, the alterations to the rock that occur during and after repository operation are also critical to evaluating the degree of risk associated with waste disposal. It is also important to evaluate aspects of repository construction and excavation, such as the number and size of shafts and boreholes as well as the repository backfill material.

The third subsystem, the groundwater flow system, includes the overlying and underlying aquifers and their hydrologic and geochemical characteristics. This subsystem is discussed in Chapter 3.

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2.1 Engineered Controls

2.1.1 Waste Form

We considered two types of waste: solidified high-level waste which results from reprocessing spent fuel to recover uranium and/or plutonium, and spent fuel itself. The engineering controls for spent fuel disposal could be limited to containment of the fuel in an outer steel canister purged and backfilled with dry nitrogen (ADL 79b), or additional procedures could be used, such as casting metal into the spent fuel canister. The high-level liquid waste resulting from spent fuel reprocessing would be solidified in a stable matrix, such as glass. The most important single characteristic of either of these waste forms is the rate at which they release radionuclides into groundwater in the repository. For certain radionuclides, this release rate may be limited by their solubility in groundwater. Solubility limits are discussed in detail in Chapter 4. To simplify our analysis of releases from the waste package, we selected a reference waste form which incorporates the most important characteristics of both spent fuel and reprocessed waste.

We also simplified our analysis by considering only a few of the radionuclides which would be buried in a repository. The modified inventory is based on a detailed computer analysis with the ORIGEN computer program (BE 73) that was conducted by ADL (ADL 79a). This analysis revealed that many of the hundreds of radionuclides which were evaluated could be omitted from further consideration. The criteria for including a radionuclide in our analysis is either the large quantity of radioactivity, large dosimetric significance, long half-life, and/or short retention times by the geologic media. The inventory of radionuclides we analyzed is presented in Table 2-1. Further discussion of the repository inventory is included in Appendix A. We used the radionuclide mixture contained in spent fuel to characterize the waste since it has a higher inventory of many important radionuclides and represents a more concentrated heat source.

To develop a reference waste form release rate (which we sometimes call a "leach rate"), ADL reviewed the effectiveness of various waste forms (ADL 79b). The scope of this study, which considers high-level liquid wastes, cladding hulls and fuel handling residues, and spent fuel elements is illustrated in Table 2-2. We considered only high-level waste and spent fuel in this report since the other waste categories involve much less radioactivity.

To develop a reliable reprocessed waste form, solidification of the waste liquid could be performed by calcination followed by glassification (ADL 79b). Calcination occurs when the liquid waste is roasted at high temperatures to produce a granular powder that is stable and less mobile than liquid wastes, but is still highly leachable. Calcines are relatively soluble and have high surface-area-to-mass ratios. Since full dissolution of calcined waste would be expected to occur in less than one year, the calcined waste should be converted to glass to limit dissolution. Calcined waste is glassified by melting the waste together with glassmaking frits

Table 2-1

Cnaracteristics of Radioactive Waste

(Spent Fuel)

Radionuclide	Initial Quantity in Repository (ADL 79a) (curies)	Half Life (years)
Am-241	1.7 E8	458
Am-243	1.7 E6	7,650
C- 14	2.8 E4	5,730
Cs-137	8.6 E9	30
I-129	3.8 E3	1.6 E7
Np-237	3.3 E4	2.14 E6
Pu-238	2.2 E8	89
Pu-239	3.3 E7	24,400
Pu-240	4.9 E7	6,260
Pu-242	1.7 E5	3.8 E5
Sr- 90	6.0 E9	29
Tc- 99	1.4 E6	2.1 E5
Sn-126	5.6 E4	1.0 E5
Zr- 93	1.9 E5	9.5 E5

Table 2-2

Various Waste Forms†

Source of Waste	Converted Waste Form	Assumed Mode of Disposal	Canister Material	Notes
High Level Liquid Waste	calcine	deep geologic burial	(a) carbon steel	spray calcination process
			(b) titanium	spray calcination process
	borosilicate glass	deep geologic burial	stainless steel	in-can melt process
Spent Fuel	none	deep geologic burial	(a) carbon steel	dry nitrogen backfill
			(b) titanium	dry nitrogen backfill
Cladding Hulls*	none	deep geologic burial	carbon steel	compacted to 1/3 original volume
Krypton-85	none	storage at reprocessing plant	steel (pressure cylinders	stored for ~100 years for decay
Iodine-129	none	deep geologic burial	carbon steel	as silver zeolite and mercuric iodate
Carbon-14	none	deep geologic burial	carbon steel	as calcium carbonate
Tritium		release		

---

*For this study fuel bundle hardware is assumed to be separated from cladding hulls and treated as low-level waste.

†Based on information from the ADL report (ADL 79b, ADL 79c).

to form a relatively homogeneous mixture of waste products in glass. Many years of laboratory work have shown that glass leaching is usually a very slow process. The theoretical models and physical data, however, are often conflicting, imprecise, and incomplete. Studies of the effects of factors such as temperature, flow, pH, and salinity on various types of glass are currently under investigation (ME 81). The extrapolation of the short-term laboratory tests to very long time periods is hindered, however, by the limited amount of long-term leaching data available. The adequacy of short-term leach rate data to represent long-term processes needs to be evaluated. Several different sources of leach data for glass have been reviewed by ADL (ADL 79b) and are summarized in Table 2-3.

Since the data are so sparse, it appears prudent to assume a conservative (i.e., high) value for glass leach rates. A value of 10^{-6} g/cm^2 per day has been chosen as the reference value for this report. This value is larger, by at least a factor of seven and as much as a factor of 100, than any reported leach rates measured one-year after initiation of leeching (ADL 79b,c). We assume no change in the leach rate with time--resulting in a constant fractional radionuclide release rate for our analyses. We believe our conservative approach should compensate for any uncertainties concerning long-term deterioration of the waste package, such as devitrification.

Table 2-3

Glass Leach Rate Constants (gm glass/cm^2-day)

Source:	Leach Period - Days					
	1	20	115	300	700	2900
Mendel[(A)]						
Based on Cs and on Sr	10^{-6}		10^{-7}			
Ross[(B)]						
Based on Soxhlet Test: (Time not indicated)		10^{-5}				
Based on Cs	10^{-6}	4×10^{-7}	2×10^{-7}	1.5×10^{-7}		
Merritt[(C)]						
First Test (Glass 1)	10^{-5}	10^{-7}		10^{-8}		
Second Test (Glass 2)	10^{-5}	10^{-6}		7×10^{-8}		
Field Test (Glass 2)	4×10^{-8}				4×10^{-10}	5×10^{-11}

(A) Reference (ME 77a) Devitrification of these same glasses increased the leach rate by a factor of 10 to 20.

(B) Reference (RO 77) Soxhlet test is batch "flowing" water at approximately 90°C. Devitrification increased leach rate by up to 6 times the rate measured by the Soxhlet test.

(C) Reference (ME 77b).

To determine the total release rate of radioactive material, glass leach rates (g/cm^2 per day) must be combined with surface-to-mass ratios (cm^2/g) to give fractional releases per day. ADL assumed an initial surface-to-mass ratio of about 0.4 cm^2/g for glass. This value is consistent with test data on actual canisters considering normal cooling transients and additional breakage from normal handling. The resulting initial release rates range from roughly 0.01 percent per year down to 0.0001 percent per year, depending upon the assumed glass leach rate value.

The leach rate for spent fuel can vary widely depending upon temperature, groundwater chemistry, and oxygen content. The range reported in the ADL report (ADL 79b) spans five orders of magnitude, from 1x10^{-6} g/cm^2 per day to 0.1 g/cm^2 per day. Considerably more effort is required to increase our knowledge of spent fuel leach rates. We assume the radionuclide release rate for the spent fuel matrix is 10^{-4} yr^{-1} (0.01 percent per year). This value is based on the conservative value chosen for glass since it is expected that the eventual spent fuel matrix will have to be at least as resistant to leaching as a low leach rate material which is presently available, such as glass. To determine the importance of the release rate in disposing of radioactive waste, several other release rates were analyzed--including a low release rate for glass of 10^{-6} yr^{-1} and a high release rate of 10^{-2} yr^{-1}, which is more representative of calcines.

2.1.2 Waste Canisters

The waste matrix discussed in the previous section will be enclosed in a canister. Canister lifetimes can range from as little as several years to more than 1000 years, depending upon canister material and repository characteristics (ADL 79b). The manufacture of high-integrity canisters with expected lifetimes up to 1000 years appears to be feasible--either by using thicker sections of conventional materials, such as carbon steel or stainless steels or, in salt media, through the use of a material with a low corrosion rate, such as titanium. In this report, we briefly discuss carbon steel, stainless steel, Inconel, and titanium canisters; a more complete review is contained in ADL's report (ADL 79b). The number and spacing of canisters to be stored in the reference repository are listed in Table 2-4.

The importance of the resistance of the canister to corrosion in the geologic disposal medium depends on the degree of containment desired. To be conservative, we have assumed that in a salt repository the canister will be in a hot, moist, salt-saturated environment. We have assumed the environment of nonsalt media to be less corrosive but still hot and moist. Carbon steel and stainless steel have very poor corrosion resistance in hot brine. Although Inconel has outstanding resistance to corrosion in hot flowing seawater, it is quite vulnerable to pitting and serious localized attack in quiescent seawater. The corrosion rates of mild steel range from 0.08 to 1.6 mm yr; rates for Inconel alloys range from 0.0008 to 0.134 mm yr; and stainless steel corrosion rates range from 0.0001 to 0.97 mm yr (ADL 79b). Titanium and its alloys are outstanding

Table 2-4

Reference Repository Parameters

Depth of Repository		460 m
Dimensions of Repository	width	2 km
	length	4 km
	height	5 m
Number of Canisters		35,000
Number of Waste Drifts		350
Canisters per Waste Drift		100
Length of Waste Drift		500 m
Canister Spacing		5 m
Total mined volume		10^7 m^3

in their resistance to corrosion by seawater under all conditions of temperature and velocity. Titanium corrosion rates in hot salt water are on the order of 0.002-0.02 mm per year--the lower rate applies to titanium alloys, and represents a service life of 1000-10,000 years for a 25 millimeter thick canister (ADL 79b).

Since we do not know what the final design characteristics or capabilities of the canister will be, we have taken a conservative approach. We assumed a canister life of 100 years for salt media, and a 500-year canister life for less corrosive host rocks. To simplify our analysis, we have also assumed that all the canisters fail simultaneously and completely at the end of their assumed life. To determine the sensitivity of our analysis results to canister life expectancy , we also analyzed canister lives of 1000 years and 5000 years.

2.2 Geologic Media

Based on the efforts being conducted by the Department of Energy, ADL concentrated its study on the following five geologic host media (ADL 79b).

1) bedded Salt; stratified, plastic
2) domed Salt; intrusive, plastic
3) granite; intrusive, fractured
4) basalt; stratified, fractured
5) shale; stratified, fractured

Other rock types have been considered for repositories, such as welded volcanic tuffs, desert alluvium, annydrite, and seabed sediments (ADL 79d). Nevertheless, the media included in the ADL report span a wide range of geologic structure and rock properties, and we believe an analysis based on them is representative of the performance capabilities of geologic repositories in general.

The host media are generally overlain with several hundred meters of earth, usually silt, shale, or sand, and bounded above and possibly below by aquifers. The host rock is either stratified (such as bedded salt, shale, or basalt) with an aquifer above and below, or is an intrusive (such as granite or domed salt) with only an aquifer above the repository. The host rock characteristically is either plastic and tends to move under earth pressures, or structurally very rigid but susceptible to fracturing. The host rocks that are plastic (bedded salt, domed salt, some shales) are almost impermeable to water and, if fissures in the rock occur, the rock tends to reseal itself. The host rocks that are structurally rigid (granite, basalt, most shales) have low permeabilities, but can be fractured, especially as a result of faulting or thermal change, and they do not reseal themselves. All of these host rocks are good heat conductors, with salt being the best dissipator of heat.

2.2.1 Bedded Salt

More research has gone into analyzing bedded salt as a suitable waste repository medium than for any other lithology. One of the more attractive features of bedded salt is its common occurrence in stable formations at depths considered for repositories (200 meters to 1000 meters). It possesses the following properties: (1) it is very soluble, which is not a good characteristic for a waste repository; (2) it is plastic under pressure, thus tending to creep into voids and cracks and seal itself to the flow of water; and (3) it is the best thermal conductor of the five media.

Salt is frequently mined and is often associated with other minerals, oil or gas. However, because bedded massive salt deposits are numerous in the United States, sites can probably be found which have minimal economic value and a range of other desirable characteristics. ADL developed a generic bedded salt repository which is schematically represented in Figure 2-1 (ADL 79d). The reference repository is 460 meters deep, in the middle of a homogeneous bed of salt 100 meters thick, with overlying and underlying aquifers. The salt is bounded by layers of shale which are 50 meters thick.

2.2.2 Domed Salt

Some salt formations have been forced up through overlying rocks from original beds several thousands of meters deep. These domes or stacks of salt are composed of fairly homogeneous halite and are generally devoid of the interbeds or similar features found in bedded salt. Typically, a salt dome will be roughly a kilometer in diameter and capped with a blanket of less soluble evaporite.

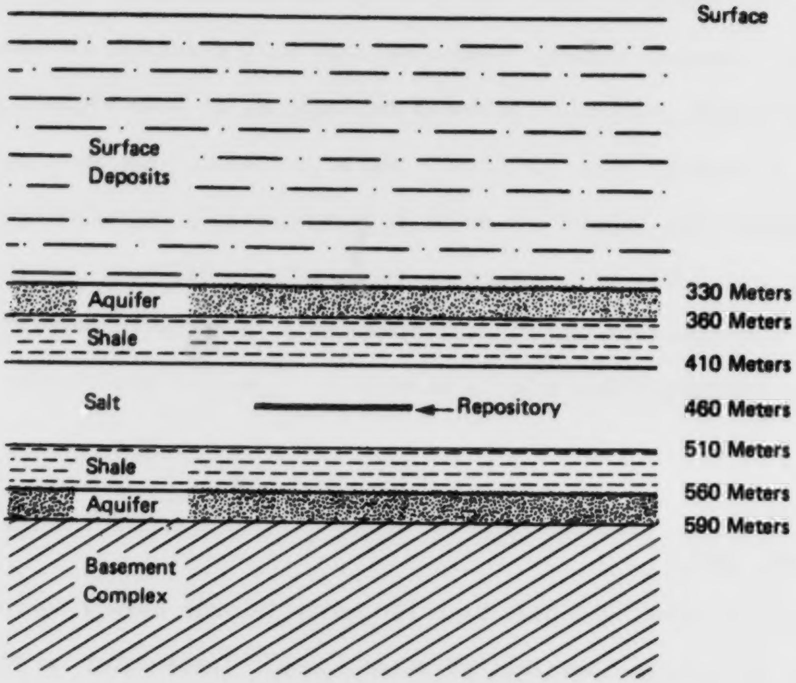
Surface
Surface Deposits
330 Meters
Aquifer
360 Meters
Shale
410 Meters
Salt
Repository
460 Meters
510 Meters
Shale
560 Meters
Aquifer
590 Meters
Basement Complex

FIGURE 2-1: REFERENCE REPOSITORY IN BEDDED SALT

Because the dome was injected through the overlying strata, the rock surrounding the dome is often shattered and disrupted with prevalent joints and fractures. The salt itself may come very near to, or even reach, the surface, but the source of the salt column may extend to a depth of 10 kilometers. The geometry of a dome prevents an aquifer from being directly below the repository. However, the fracturing of the surrounding rock causes the salt to be in contact with groundwater in adjacent aquifers. These and other differences between bedded and domed salt deposits require separate analyses for each. As with bedded salt deposits, domes are frequently associated with oil, gas, and various mineral resources. In addition, salt domes are often mined for their relatively pure salt or used as storage caverns.

Figure 2-2 is a schematic illustration of the reference domed salt repository described by ADL (ADL 79d). The repository is 460 meters below the earth's surface in the middle of a homogeneous salt dome. The overlying aquifer is assumed to be identical to the one for bedded salt at a depth of 200 meters. The lower aquifer surrounds the dome at 560 meters.

2.2.3 Granite

Granite, which is a monolithic crystalline rock, is another potential host medium. It is an assemblage of minerals forming a rigid and essentially insoluble rock. It is relatively strong and does not flow plastically; thus, cracks can remain open to migrating fluids, although some cracks may become filled with clay or other materials. In addition,

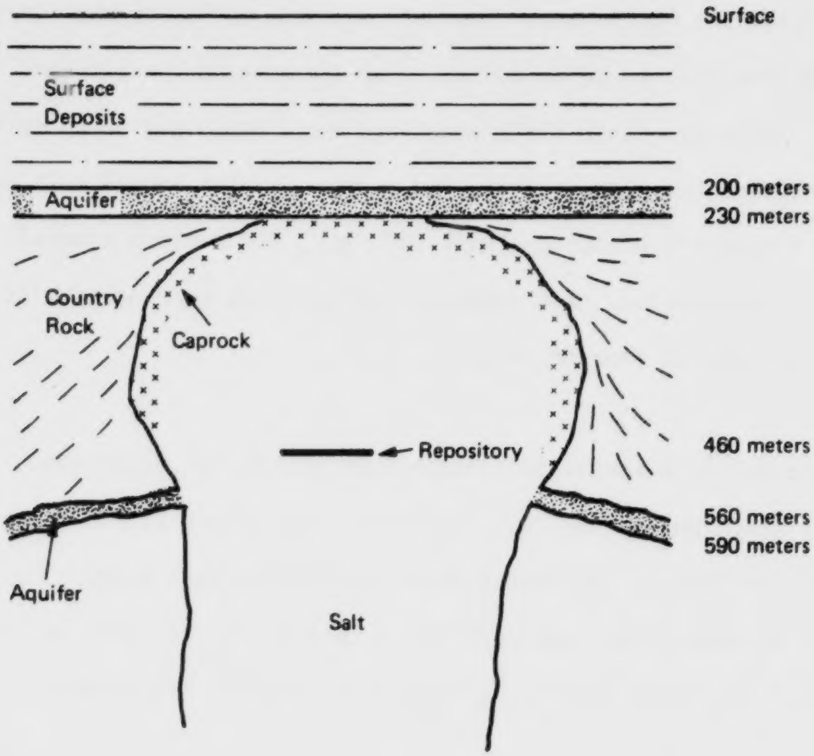
Surface
Surface Deposits
200 meters
Aquifer
230 meters
Country Rock
Caprock
Repository
460 meters
560 meters
590 meters
Aquifer
Salt

FIGURE 2-2: REFERENCE REPOSITORY IN DOMED SALT

water passing through granite is generally less corrosive than the brines associated with salt. Because it is intrusive and not underlain by stratified deposits, the granite repository would not generally have an underlying aquifer. This affects the analysis of water flow through the repository.

Many areas of the country have granite or similar rocks at depths suitable for a repository. Occasionally, vein minerals, pegmatites, or quarry stone make granite economically important, but the vast expanse of crystalline rocks suggests that many potential site locations exist.

Figure 2-3 is a schematic illustration of the reference granite repository described by ADL (ADL 79d). The reference granite repository is 460 meters below the earth's surface. The overlying aquifer is assumed to be identical to the one for bedded salt, but at a depth of 200 meters.

2.2.4 Basalt

Basalt is another igneous rock that is being considered as a repository medium. It shares with granite many properties common to igneous rocks. It is strong, rigid, highly resistant to dissolution, and has a complex mineralogy.

The extensive flow basalts currently being investigated are unlike other igneous rocks in a number of important ways. These basalts have formed as a series of layers over a long period of time and there are sedimentary interbeds and other permeable zones that can serve as aquifers

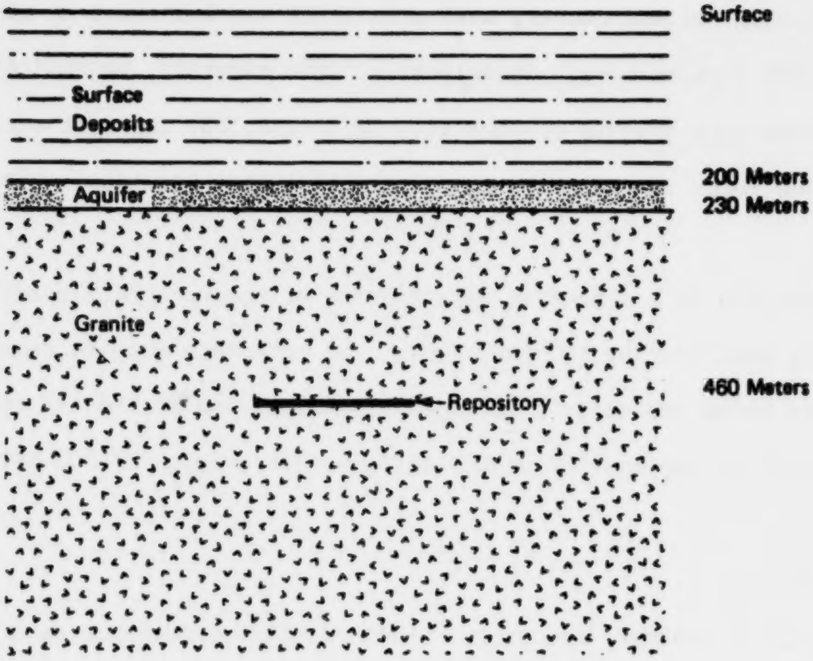
Surface
Surface Deposits
200 Meters
Aquifer
230 Meters
Granite
460 Meters
Repository

FIGURE 2-3: REFERENCE REPOSITORY IN GRANITE

contained within them. These aquifers could exist both above and below any basalt flow in which the repository would be located. Basalt characteristically breaks into slender columns as it cools, producing vertical joints. However, weathering products of the rock often fill these joints. Basalt is rarely associated with other mineral resources, and its most common economic use is as fill material. The principal flow basalts that are being investigated for possible repository siting are located in southeastern Washington.

Figure 2-4 is a schematic representation of a reference basalt repository (ADL 79d). The reference repository is 460 meters below the earth's surface with 100 meters of basalt above and below the repository. The basalt is bounded by overlying and underlying aquifers at 330 meters and 560 meters, respectively. The two aquifers are identical to those for the reference bedded salt repository.

2.2.5 Shale

Argillites, siltstones, and shales are the most common and extensive sedimentary rocks. These clay-rich rocks are found in thick deposits, and they are often nearly impermeable. Some shales exhibit a plastic behavior similar to salt, and they have the added advantage that they are essentially insoluble. The hydrologic and geochemical properties of shales vary considerably.

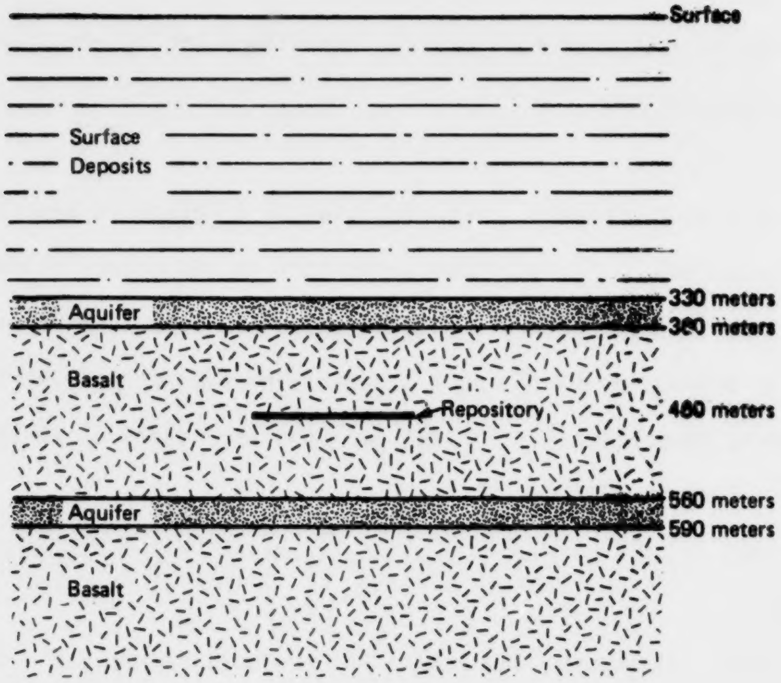
Surface
Surface Deposits
330 meters
Aquifer
360 meters
Basalt
Repository
460 meters
560 meters
Aquifer
590 meters
Basalt

FIGURE 2-4: REFERENCE REPOSITORY IN BASALT

Clay minerals have a number of properties that may be important to waste containment. Several clays can absorb water into their structures, swelling in the process and sealing pore spaces and potential water passageways. Similarly, clays can absorb chemicals, including radionuclides, and severely retard their movement. Many clay minerals, however, can also be dehydrated by heating. This process could change both their chemical and mechanical properties, thereby affecting their ability to contain wastes.

Argillaceous (clay-containing) deposits have a variety of economic uses. Their abundance, however, suggests that many potential sites could exist where economic and social impacts would be minimal. We assume the reference shale repository is highly indurated, which would aid the stability of a mine while perhaps increasing the potential for fluid flow through fractures. While some shales are nearly impermeable to the flow of water, the hard shale in the model is assumed to have hydrologic properties similar to that of basalt.

Figure 2-5 is a schematic representation of a reference shale repository. The schematic is identical to the one for bedded salt except that a shale layer replaces the salt layer.

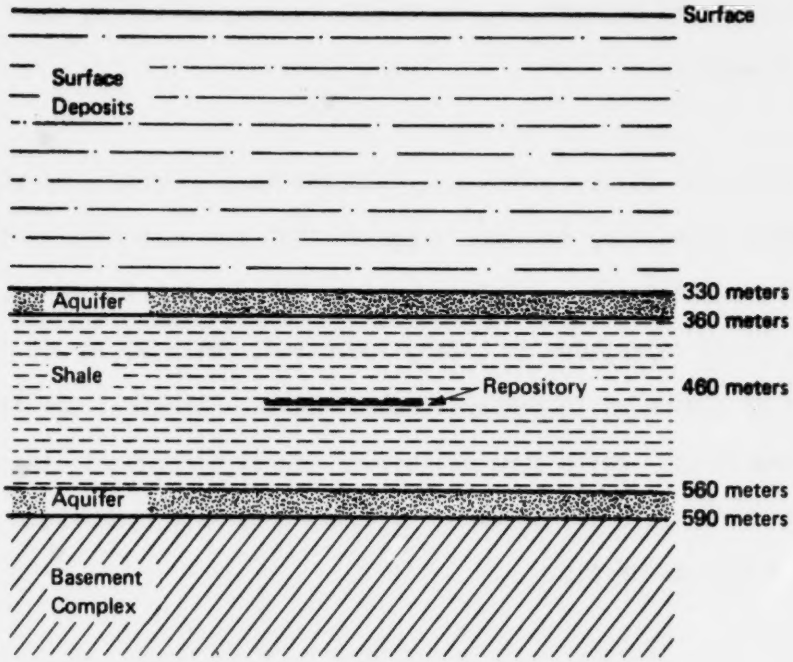
Surface
Surface Deposits
Aquifer
330 meters
360 meters
Shale
Repository
460 meters
Aquifer
560 meters
590 meters
Basement Complex

FIGURE 2-5: REFERENCE REPOSITORY IN SHALE

2.3 Repository Construction

The ADL report discusses many aspects of repository construction and the design of the mined tunnels, boreholes, shafts, etc. (ADL 79b). However, the only construction characteristics considered in this analysis are the repository backfill and the borehole and shaft seals.

During repository excavation, all of the mined material may be brought to the surface, stored during emplacement of the wastes, and then used as backfill for the tunnels. Alternatively, if a working mine volume has been created, mined material from a tunnel under construction may be used immediately as backfill for a tunnel already loaded with waste. In either case, based on a mined fraction of 25 percent and a repository height of 5 meters (ADL 79d), the volume of backfill would be $1x10^7$ m^3. Since the backfill cannot be packed very tightly, we assume the porosity of the backfill is 20 percent. Thus, the porosity volume would be $2x10^6$ m^3. After backfilling the repository, if any water is available the backfill can become recharged with water. This recharge water can be supplied through the surrounding bulk rock and/or by the migration of water through permeable borehole and shaft seals. In salt repositories the undisturbed salt is essentially impermeable to the flow of water. Thus, the recharge of the backfill would only occur through the shafts and boreholes.

During the operational stage several vertical shafts and many boreholes will be required for ventilation, exploration, and transportation of personnel and materials between the mine and the surface. Sealing the repository to isolate the radioactive waste requires that these shafts and boreholes be filled to prevent them from serving as conduits for fluid flow and radionuclide migration. The sealing materials will probably have chemical and mechanical characteristics very similar to those of the surrounding rock. The seal may consist of several layers of completely distinct types of materials to provide redundant barriers to intrusion. Nevertheless, it is reasonable to expect that--over a long period of time--the combination of processes such as settling, leaching, expansion and contraction due to fluctuations in water content or temperature, earth movements, weathering, and fatigue may lead to some degradation in the integrity of the seal. We represented this degradation with a generic model that characterizes the shaft seal integrity by a spatially uniform hydraulic conductivity K. One hydraulic conductivity value (K_0) is assumed for the time of seal placement, and another value (K_1) is projected for the time 10,000 years later. We then assume that K increases linearly from K_0 to K_1 over this period (ADL 79d).

Chapter 3 - GROUNDWATER TRANSPORT

There are several models which have been developed to describe the complicated movement of radionuclides from a repository to an aquifer and then through the aquifer to a river or other body of surface water (ADL 79c). These models often require extensive data and generally calculate the concentration of radionuclides at specific locations and for specific times. However, our analysis of population risks, which requires only the calculation of total releases to the environment, can use simpler models. One of our principal considerations is the time required for radionuclides to travel from the repository to the environment. This chapter describes our simplified model and compares it with more sophisticated models. We discuss the specific parameters we used--especially those describing the reference aquifer, the hydraulic gradients, and the hydraulic conductivity and porosity of the host rock.

3.1 Basic Model

The transport of radionuclides from a deep geological repository through the groundwater pathway to the biosphere depends on the hydrological and geochemical properties of the aquifers overlying and underlying the repository and the path from the repository to these aquifers. A schematic of the groundwater model we used is shown in Figure 3-1. We made the following assumptions in developing our reference groundwater model:

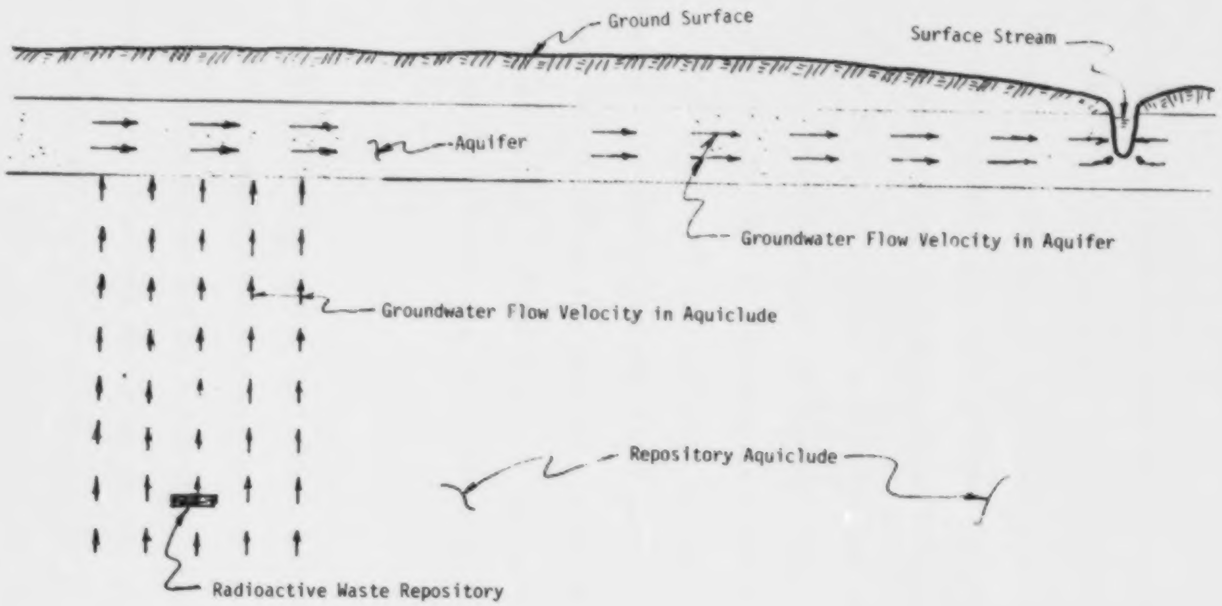
Ground Surface
Surface Stream
Aquifer
Groundwater Flow Velocity in Aquifer
Groundwater Flow Velocity in Aquiclude
Repository Aquiclude
Radioactive Waste Repository

FIGURE 3-1: SCHEMATIC OF GROUNDWATER MODEL

1. The waste will be disposed in geological formations with very low hydraulic conductivities. For this analysis these formations can be lumped together and considered to be a single host formation.
2. Generally, aquifers lie above and beneath the host formation. For intrusive geologic media such as granite and domed salt there is no aquifer below the host rock. However, domed salt formations are assumed to have a "lower" aquifer surrounding the dome below the level of the respository. There is no lower aquifer for granite.
3. The upper and lower aquifers are confined by relatively low permeability layers of rock and they deliver a steady groundwater flow over the entire time of interest.
4. The hydrologic and geohydrologic characteristics of the upper and lower aquifers are identical except for the potentiometric head. The hydraulic gradient between the aquifers caused by the potentiometric head difference is assumed to be constant. The potentiometric head in the lower aquifer is assumed to be greater than the head in the upper aquifer, and flow is from the lower to the upper aquifer.
5. A buoyant force is assumed to result from a temperature difference and is designated as a thermal buoyancy gradient. This is dissussed further in Section 3.2.

Based on these assumptions, the radionuclides being released from the repository into the groundwater will be transported upward through the host formation to the upper aquifer. The radionuclides are then slowly transported horizontally through the upper aquifer to a body of water on the earth's surface, such as a lake or river, where they become available to people.

For simplicity, we chose two one-dimensional ground water transport models to describe transport through the host material and the aquifer. One represents vertical transport through the host rock and depends on the area, hydraulic conductivity, and gradient of boreholes, shafts, or fractured host rocks; the other represents horizontal transport through the aquifer and depends on the properties of the aquifer. The basic assumptions used to describe the one-dimensional transport of a radionuclide through a homogeneous medium are:

1. The flow in the geological formation is laminar and one-dimensional. The restriction that Darcy's law is valid only under conditions of laminar flow, and that it requires modification when turbulent flow prevails, should not affect analyses for a suitable repository site. Even though turbulent flow conditions may exist on a microscopic basis as groundwater moves through geologic media, the macroscopic flow in generally low permeability regimes (such as should exist in the geologic media surrounding any reasonable site for a repository) may be adequately described by the laws governing laminar flow (Darcy's Law).

2. The driving forces which transport the groundwater and radionuclides through the host rock are a combination of the buoyant force resulting from the thermal gradient plus the hydraulic gradient which exists between the upper and lower aquifer.
3. Equilibrium between the sorbed and dissolved radionuclides within the groundwater system is maintained at all times. That is, the rate of reaction for the sorption process is much faster than that of the radionuclide migration and radionuclide decay.
4. Hydrodynamic dispersion remains constant and is independent of the concentration gradient. Furthermore, we decided that dispersion may be neglected in this risk assessment. Details of the evaluation leading to this judgment are presented in Appendix B.

The equation which describes one-dimensional transport of a single radionuclide in a homogeneous medium is:

$$\frac{\partial C}{\partial t} - \frac{D\partial^2 C}{R\partial x^2} + \frac{v\partial C}{R\partial x} + \lambda C = 0 \qquad (3\text{-}1)$$

where C is the concentration of the radionuclide as a function of distance x and time t, D is the coefficient of hydrodynamic dispersion, v is the interstitial velocity of the groundwater, λ is the radioactivity decay constant, and R is a retardation factor which is a function of the physical and geochemical interaction of radionuclides with the geologic media. The coefficient of hydrodynamic dispersion, D, refers to the spreading and mixing which is caused in part by the bulk movement of groundwater and molecular diffusion. For many field situations the mixing caused by the bulk movement of groundwater is most important, but in low velocity systems, such as are expected near a repository, molecular diffusion is the dominant process affecting hydrodynamic dispersion. In the absence of hydrodynamic dispersion the physical and geochemical interactions of radionuclides with the geologic media can significantly affect the rate of radionuclide transport. For example, if the retardation factor, R, equals 10, the radionuclide is transported slower than the groundwater by a factor of 10.

If the dispersion effects are small and can be ignored, then equation 3-1 can be written:

$$\frac{\partial C}{\partial t} + \frac{v \partial C}{R \partial x} + \lambda C = 0 \qquad (3\text{-}2)$$

This equation can be rewritten to describe the rate of total radionuclide activity being transported by introducing:

$$\dot{Q} = CA\eta v \qquad (3\text{-}3)$$

in which $\dot{Q}$ is the rate of total activity being transported through distance x at time t, η is the porosity of the geological medium, v is the interstitial velocity, which is assumed to be constant along the flow path, and A is the cross-sectional area of the flow path. Substituting equation 3-3 in equation 3-2 results in:

$$\frac{\partial \dot{Q}}{\partial t} + \frac{v \partial \dot{Q}}{R \partial x} + \lambda \dot{Q} = 0 \qquad (3\text{-}4)$$

Equation 3-4 is the basic differential equation for the groundwater transport model and can be solved either numerically or analytically when the interstitial velocity is known and the boundary and initial conditions are defined.

3.1.1 Host Formation Model

The repository may be exposed to natural or man-caused disruptions that result in abrupt or gradual changes in the hydraulic conductivity of a portion of the host formation. Should these disruptions ever occur, we have assumed that the hydraulic gradient across the host formation would be upward. The groundwater interstitial velocity appearing in equation 3-4 can be described as:

$$v = Ki/\eta \qquad (3\text{-}5)$$

where K is the hydraulic conductivity, η is the effective porosity, and i is the hydraulic gradient across the host formation. The hydraulic gradient in this equation represents the combined effects of the aquifer interconnections (assumed to create an upward gradient) and the temperature effects, as stated previously.

Since the heat generated from the waste will vary with time, the fluid properties, such as viscosity and density will change with time--as will the interstitial velocity. The relatively slow rate of change of velocity, however, allows a quasi-steady state solution to equation 3-4 by assuming that the velocity is constant over time. The resulting analytical solution is:

$$\dot{Q}_{aq} = \dot{Q}[t - t_e - R_1x_1/v_1] \text{ EXP } (-\lambda R_1x_1/v_1) \text{ U}[t - t_e - R_1x_1/v_1] \tag{3-6}$$

where t_e is the time the release occurred, x is the vertical distance between upper aquifer and the waste repository, the subscript 1 denotes the host formation, and Q_{aq} is the rate of release to the aquifer. The U term is a step function. The amount of radioactivity which would reach the aquifer is the same as the amount leaving the repository, corrected for radioactive decay during transit. For the host media and barrier seals, R_1 is conservatively assumed to be 1 for all the radionuclides. Because the distance from the repository to the aquifer is a small fraction of the distance to the environment, the analysis results are not sensitive to values of R_1.

3.1.2 Aquifer Model

The most important aspect of the aquifer is the radioactive decay which occurs during transit from the host rock to the environment. We make the assumption that the hydraulic gradient and hydraulic conductivity of the upper aquifer remain unchanged regardless of any disturbance of the repository. We derive the aquifer transport model from our basic differential equation 3-4. The analytical solution for equation 3-4, using equation 3-6 as a boundary condition, is:

$$\dot{Q} = \dot{Q}[t-t_e-t_d] \text{ EXP}[-\lambda t_d] \text{ U}[t-t_e-t_d] \tag{3-7}$$

where:

$$t_d = t_{d1} + t_{d2} = R_1x_1/v_1 + R_2x_2/v_2$$

The subscript 2 denotes the aquifer, and the other variables have been defined previously. The rate of radionuclide release into the surface water from the aquifer therefore can be estimated by using equation 3-7.

For modeling aquifer flow we assume there is no difference between the aquifers of the five types of geologic repositories. Table 3-1 presents the reference aquifer characteristics and their range of values. These values are taken from the ADL report (ADL 79c) and are representative, for example, of sandstone formations with low-to-moderate hydraulic conductivity.

Transport of radionuclides to the environment is dependent on the ability of the overlying and underlying aquifers to transmit water. Groundwater moves from points of higher head to points of lower head, and the flow rate is directly proportional to the hydraulic gradient. The relationship between the hydraulic gradient and the groundwater flow rate is expressed by Darcy's Law:

$$V_{aq} = (KiA)_{\text{aquifer}} \tag{3-8}$$

where: V_{aq} = aquifer volumetric flow rate, m^3/yr
K = hydraulic conductivity of the aquifer, m/yr
i = hydraulic gradient of the aquifer
A = cross-sectional area of the aquifer, m^2

Using the parameters in Table 3-1, the limiting aquifer flow rate is calculated to be 37,800 m^3/yr, and the interstitial velocity is calculated (equation 3-5) to be 2.1 m/yr.

Table 3-1

Aquifer Characteristics

		Reference values	Range of values
Distance from repository to overlying aquifer (meters)	bedded salt, basalt	100	-----
	granite, domed salt	230	-----
Distance along aquifer to man's environment (meters)		1600	-----
Hydraulic conductivity in aquifer pathway (meters/year)		31.5	.31-31.5
Gradient in aquifer pathway		.01	.01-0.1
Effective porosity in aquifer pathway		.15	.15
Cross-sectional area of aquifer overlying the repository (square meters) (normally the thickness of the aquifer times the widest dimension of the repository floor area)		1.2E5	-----
Thickness of aquifer (meters)		30	15-45

The travel time in our reference aquifer from the host rock to the environment can be calculated using equation 3-9:

$$t_{d2} = (R_2 x \eta)/(Ki)_{aquifer} \qquad (3\text{-}9)$$

where K and i are the hydraulic conductivity and gradient of the aquifer, x is the distance to the environment from the repository, and η is the porosity of the aquifer. Using the appropriate parameter values from Table 3-1, the aquifer travel time for R_2 equal to 1 is calculated to be about 762 years. If the retardation factor were higher by a factor of 10, the travel time would be 7620 years.

3.2 Gradients: Host Rock

The driving forces for transporting water from a repository to an overlying aquifer are the combination of the hydraulic gradient between the overlying and underlying aquifers and an additional gradient caused by thermally induced buoyancy. For salt repositories, the lithostatic pressure from the overburden can also force groundwater in the repository up through shaft seals to the overlying aquifer. The pertinent aspects of these forces and their appropriate application are briefly described in this section--and are discussed further in Chapter 5 for specific releases.

We assume the hydraulic gradient between the aquifers is upward to provide a worst-case analysis. If a downward gradient did exist, it would represent a more favorable condition--since any flow would then be to strata at greater depths. ADL (ADL 79d) estimated the upward gradient between aquifers to be between 0.01 and 0.5. We have assumed that 0.1 would be a conservative gradient for our evaluation.

The heat generated by the decay of radioactive waste in a repository affects the viscosity and density of any water present. These changes in water properties affect the volumetric flow of groundwater from the repository to the overlying aquifer. To calculate the volumetric flow, equation 3-8 can be modified by replacing the gradient term with the product of a viscosity correction factor, $c(\mu)$, and the sum of the original hydraulic gradient and a thermally induced buoyancy gradient.

ADL provided values of the viscosity coefficient, μ, of the water as a function of temperature and time since sealing of the repository (ADL 79d). These values are presented in Table 3-2. The viscosity correction factor, $c(\mu)$, is dimensionless and is the ratio of the viscosity of water at 20°C to its viscosity at the temperature of interest. The viscosity of water at 20°C is 0.01 poise, thus $c(\mu)$ can be represented as the inverse of the viscosity at the specified temperature multiplied by 0.01. The right hand column of Table 3-2 is an analytic approximation to the time-gradient viscosity data points. The change in water density caused by the heat generated by the decay of radioactive waste results in a buoyant effect that creates an upward force from the repository to the upper aquifer (ADL 79d)--resulting in corrective movement of water. The equivalent gradient resulting from this buoyancy effect depends on the time dependent temperature of the repository. The average density of the water column extending from the repository to the aquifer was estimated to

Table 3-2

Equivalent Gradient and Viscosity Coefficient for Aquifer Interconnection[*]

time, years	temperature (at 350m), °C	viscosity, μ, poise	$c(\mu)$	$i_a c(\mu)$**	$i_a(ce^{-\gamma t}+1)$**
100	120	.0023	4.35	.43	.38
200	111	.0026	3.85	.38	.37
300	106	.0027	3.70	.37	.36
400	102	.0029	3.45	.34	.36
500	99	.0029	3.45	.34	.35
1000	90	.0033	3.03	.30	.32
2000	72	.0039	2.56	.26	.27
3000	61	.0047	2.13	.21	.23
4000	54	.0050	2.00	.20	.20
5000	48	.0056	1.79	.18	.18
10000	30	.0082	1.22	.12	.12

---

[*] The reference granite repository does not have an underlying aquifer; therefore, i_a is zero for that case.

[+] The assumed gradient and calculated viscosities are taken from the ADL report (ADL 79d).

[**] $c = 2.88$
$\gamma = 2.6 \times 10^{-4}$
$i_a = 0.1$

be approximately the same as the water density at a depth of 350 m for all times after about 100 years. ADL has estimated this thermally induced equivalent gradient as a function of temperature and time (ADL 79d) and it is presented in Table 3-3. The right hand column represents an analytic approximation to the time, thermal buoyancy gradient and viscosity coefficient data. The equation for this approximation for the thermal buoyancy term is:

$$i_b c(\mu) = a e^{-\alpha t} + b e^{-\beta t} \tag{3-10}$$

where: i_b = thermal buoyancy gradient
$c(\mu)$ = viscosity correction factor
a = 0.132
b = 0.102
α = 1.6×10^{-3}
β = 3.1×10^{-4}

and the equation for the aquifer interconnection gradient is:

$$i_a c(\mu) = i_a \; c e^{-\gamma t} + 1.0 \tag{3-11}$$

where: i_a = aquifer interconnection gradient
$c(\mu)$ = viscosity correction factor
c = 2.83
γ = 2.6×10^{-4}

To include the viscosity and density effects on the volumetric flow of water from the repository to the overlying aquifer, equation 3-8 can be rewritten as:

$$V_{aq} = K \, i^* A \tag{3-12}$$

where: $i^* = i_a \, c(\mu) + i_b \, c(\mu)$

Table 3-3

Equivalent Gradient and Viscosity Coefficient due to Thermal Buoyancy

time, years	temperature (at 350m), ^{o}c	thermal buoyancy gradient^{+} i_b	viscosity^{+}, μ, poise	$c(\mu)$	$i_b c(\mu)$	$ae^{-\alpha t}+be^{-\beta t}$ *
100	120	.057	.0023	4.35	.25	.21
200	111	.050	.0026	3.85	.19	.19
300	106	.046	.0027	3.70	.17	.17
400	102	.042	.0029	3.45	.14	.16
500	99	.041	.0029	3.45	.14	.15
1000	90	.035	.0033	3.03	.11	.10
2000	72	.023	.0039	2.56	.06	.06
3000	61	.020	.0047	2.13	.04	.04
4000	54	.014	.0050	2.00	.03	.03
5000	48	.011	.0056	1.79	.02	.02
10000	30	.004	.0082	1.22	.005	.005

* $a = 0.132$
$b = 0.102$
$\alpha = 1.6 \times 10^{-3}$
$\beta = 3.1 \times 10^{-4}$

+ The calculated viscosities are taken from the ADL report (ADL 79d).

Lithostatic pressure is applied by the overburden to each of the five repositories. The only significant potential release of radioactivity to the overlying aquifer resulting from the effects of lithostatic pressure occurs in the salt repositories. When subjected to loads for extended time periods, salt undergoes gradual plastic deformation subsequent to the initial elastic and plastic response. This gradual deformation is known as salt creep. The ADL report (ADL 79d) analyzed the significance of salt creep and estimated that the effect of salt creep would be to reseal the reference salt repository in about 200 years. Chapter 5 of this report discusses the relationship of the lithostatic pressure and shaft seal leakage for salt repositories.

3.3 Hydraulic conductivity: Host Rock

The hydraulic conductivity used in equation 3-5 for the host rock can either be (1) the primary hydraulic conductivity of a porous rock medium; or (2) the secondary hydraulic conductivity of the rock if flow is predominantly through fractures, fissures, or other types of small discontinuities. The magnitude of the primary hydraulic conductivity is mostly dependent upon the grain size, the degree of crystallization and/or cementation, and compaction of the rock mass. Primary hydraulic conductivity reflects intact, unfractured or unbroken rocks. Secondary hydraulic conductivity reflects disturbed zones (fractures, faults, joints, solution channels, etc.) where the extent of disturbance--and not the rock itself--controls the movement of water. Since the primary hydraulic conductivity of the proposed host rock is likely to be small, secondary hydraulic conductivity is likely to be of greater concern when considering potential groundwater flow through strata surrounding a repository. Secondary hydraulic conductivity must usually be determined in field experiments from well-planned borings drilled to intersect the predominant disturbed zones in the rock. Representative values of bulk rock hydraulic conductivity for various host rock are presented in Table 3-4.

Table 3-4

Example Intrinsic Properties for Typical Repository and Associated Lithologies[*]

Parameter	Salt	Shale	Dense Basalt	Unweathered Granite
Porosity (percent)	<1	10	1-40	.05-3
Hydraulic conductivity (cm/sec)				
Ranges	+	10^{-5}-$<10^{-9}$	10^{-5}-10^{-9}	10^{-6}-$<10^{-10}$
Selected Values	+	10^{-9}	10^{-9}	10^{-10}

[*] (ADL 79c)

+ Essentially impermeable for the purposes of this study

Chapter 4 - GROUNDWATER GEOCHEMISTRY

Isolation of radioactive waste from the environment also depends on the solubility of the waste in the repository groundwater and on the retardation of radionuclide transport in the surrounding aquifers. Radionuclides with low solubility in groundwater will have restricted entry into the flow system. Consequently, their discharge rates into the biosphere will be low. We believe determining local solubility limits should be an important part of site evaluation and selection.

After moving vertically from the repository to the overlying aquifer, groundwater moves horizontally through the aquifer before reaching the environment. Some of the dissolved radionuclides may react chemically with the aquifer rock mass, and their rate of transport will be retarded. This general process is commonly represented by a retardation factor. For example, a radionuclide with a retardation factor of 2 would take twice as long to reach the environment as the water does.

Solubility limits and retardation factors are site and species dependent. Thus, for a generic assessment of radionuclide transport, we had to establish several important criteria for estimating reasonable values for solubility limits and retardation factors. First, we assumed that careful site selection procedures could result in a repository with favorable geochemistry: that is, a reducing and slightly basic (a pH greater than 7) environment. Such conditions, found in a wide range of geological environments in the continental United States, favor both retention of waste by rock in the aquifer and low solubility of many radionuclides in the repository groundwater. However, because there is considerable uncertainty associated with these parameters, we have made conservative estimates of the geochemical factors for our reference repositories. We expect that actual repository sites will have lower groundwater solubility limits and higher retardation factors for the important radionuclides in the repository. Table 4-1 presents the reference retardation factors and solubility limits used in our principal analyses.

In addition, we made separate analyses: (1) assuming no constraint on radionuclide solubility; (2) using retardation factors equal to one; and (3) assuming both of these situations at the same time. We also evaluated radionuclide transport using the much higher retardation factors derived from a report by Denham, et al. (DE 73). These higher factors also appear in Table 4-1.

4.1 Retardation Factors

The physical and chemical processes which most affect radionuclide retardation in an aquifer are ion exchange, adsorption, polymerization, colloid formation, and the chemistry and solubility of the radionuclide (AM 78). These properties characterize the potential for chemical and physical interactions between the minerals in the geologic media and the radionuclides in the groundwater. The interactions generally vary with

Table 4-1

Solubility Limits and Retardation Factors

Radionuclide	Half-Life (years)	Retardation Factors Reference	Retardation Factors Denham (DE 73)	Solubility Limits (ppm)	Solubility Limits Ci/m^3
Am-241	458	100	10,000	50	160
Am-243	7370	100	10,000	50	10
C- 14	5730	1	10	na	na
Cs-137	30.2	1	1,000	na	na
Cs-135	3 million	1	1,000	na	na
I-129	17 million	1	1	na	na
Np-237	2.1 million	100	100	.001	7.2×10^{-7}
Pu-238	86.4	100	10,000	.001	1.7×10^{-2}
Pu-239	24,400	100	10,000	.001	6×10^{-5}
Pu-240	6,600	100	10,000	.001	2.2×10^{-4}
Pu-242	387,000	100	10,000	.001	4×10^{-6}
Sr- 90	28	1	100	na	na
Tc- 99	212,000	1	1	.001	2×10^{-5}
Sn-126	100,000	10	1,100	1	3×10^{-2}
U-238	4.5 billion	100	14,300	.001	na
U-234	250,000	100	14,300	.001	na
Zr- 93	1.5 million	100	10,000	.001	2×10^{-6}

---

na - Solubility limit not used or not known.

the groundwater mineral content, pH, Eh, complexing materials, organic content, and radionuclide concentrations. The low levels of radionuclide concentration normally do not alter the geochemical properties of a geologic formation. Therefore, field and laboratory tests for geochemical factors using nonradioactive elements can be used for some of the geochemical analyses described in this report.

The characteristics of each separate geochemical interaction are extremely difficult to describe, and the technology for quantifying each process is not available at this time. To quantify the rock-water geochemical interactions, the nature of the rock surface must be specified precisely with respect to its mineral and chemical composition and the surface area per unit of mass. The measurements must be carried out under conditions similar to those expected in the natural environment. The current method of evaluating the complex physiochemical reactions is to characterize their combined effect rather than to deal with each individual process. The effect of the combined processes is commonly called sorption and is expressed by means of distribution coefficients (AM 78). The distribution coefficient represents the partitioning of a substance between solution in groundwater and attachment to the rock matrix. Use of the distribution coefficient is appropriate when the reactions that cause partitioning are fast and reversible. Distribution coefficients for porous and fractured media are given by:

$$K_d = \frac{\text{Mass of solute on the solid phase per unit mass of solid phase}}{\text{Concentration of solute in solution}} = \frac{f_m \times Lv}{f_s \times M_w} \qquad (4\text{-}1)$$

and:

$$K_a = \frac{\text{Mass of solute on the solid phase per unit area of solid phase}}{\text{Concentration of solute in solution}} = \frac{f_m \times Lv}{f_s \times F_a} \qquad (4\text{-}2)$$

where K_d and K_a are the distribution coefficients for porous and fractured media respectively, f_m is the fraction of total activity adsorbed on the media, or solid phase, f_s is the fraction of total activity in the aqueous solution, M_w is the mass of the solid phase, Lv is the volume of solution in equilibrium with the solid phase, and F_a is the total surface area of the fracture.

It is more convenient to discuss radionuclide transport using the term retardation factor, which--for a particular element--is defined as the ratio of the water velocity to the element migration velocity. The retardation factor, R, is related to the distribution coefficient by:

$$R = 1 + \frac{K_d \rho_\beta}{\eta} \qquad (4\text{-}3)$$

for porous media, and by:

$$R = 1 + K_a R_f \qquad (4\text{-}4)$$

for fractured media, when η is the pore fraction, ρ_β is the bulk density of the rock mass, and R_f is the ratio of the total surface area to the volume of the fractured medium.

Ames and Rai (AM 78) note that ". . . there is a general lack of systematic evaluation of various factors that determine element-solid matrix interactions and no information at present is available to determine the magnitude of the various factors affecting the environmental transport of radionuclides." Differences in the concentrations and types of minerals, particle size, weathering, and trace-element composition will affect the distribution coefficients for different radionuclides. A particularly serious problem in the analysis of radionuclide transport is that few investigators have controlled the oxidation potential of an experimental system (BO 79). Another problem is that few experimenters have measured or estimated the retention of radionuclides in the same geologic system for a variety of radionuclides. Thus, it is difficult to select a comprehensive and consistent set of geochemical characteristics of the reference aquifers in which the radionuclides migrate.

Denham, et al. (DE 73), provide a consistent set of retardation factors for all the radionuclides we considered in our analyses. However, Denham's factors are for a site specific (Hanford), near-surface soil under oxidizing conditions and have limited application to our analyses. We selected reference retardation factors after surveying the available data, particularly that summarized by Ames and Rai (Am 78). Our selection reflects our expectation that reducing conditions will exist in the groundwater at a selected site, and they also reflect our intent to make conservative analyses because of the limited information available (i.e., we picked retardation factors that are probably considerably lower than those that can reasonably be achieved by careful site selection). The considerations that led to our choice of reference values for each radionuclide are discussed below.

In our risk assessments, only those radionuclides with a retardation factor less than 15 will reach the environment during the time of interest. For most radionuclides under consideration, use of either our reference retardation factors or the ones contained in the Denham report will not affect the result of our analyses. Of the remaining radionuclides, the two most important are carbon-14 and tin-126. Our reference retardation factor for C-14 is 1 as opposed to a reported value of 10 (Denham 73). Since we are not sure at this time of the chemical form of C-14 in the waste, we believe our more conservative approach is warranted. Very little work has been done in evaluating the retardation factor for tin, and additional experimental work is needed. Our retardation factor of 10 is more conservative than the value of 1100 reported by Denham. We do not believe a retardation factor for tin lower than 10 is required, since we expect tin to exist as both a cation and an anion and will not be as mobile as elements that exist only as anions.

4.2 Solubility Limits

The solubilities of radioactive elements in groundwater are affected by groundwater temperature, pH, Eh, chemical and radiolytic processes. In particular, the solubility of some elements (Zr, Sn, Th, U Np, Pu, Am, and Tc) will be extremely low in a reducing environment with a neutral to basic pH (AM 78, BO 79, EDA 78, BO 75, PO 66). This is the type of groundwater geochemistry that we believe should be favored in siting a repository. However, relatively few studies of radionuclide behavior in groundwater have considered reducing environments. The work of Bondietti and Francis (BO 79) is a notable exception, and we have used results from their study. In deriving solubility limits for the various radionuclides, we also used thermodynamic data from the literature (e.g., AM 78, PO 66, RA 78).

Several factors which might increase solubility limits have not been adequately evaluated for reducing environments and are not considered in the report. For example, chemical and radiolytic processes could increase the solubility of elements above those levels predicted by classical thermodynamics. Elevated groundwater temperatures can also increase or decrease the solubility of some elements. In this report we have not considered the effects of elevated temperatures on radionuclide solubility limits. Neither have we considered the possiblity that some low solubility waste forms might chemically react with other chemicals present in the waste. We have not considered the possibility of these interactions in establishing our solubility limits because the stability of some complexes of nuclear waste elements are not known.

The ideal method of calculating radionuclide solubility is to develop simultaneous equations of all the known equilibria of the radioactive element for a site-specific groundwater and disposal geology. Runnells, et al. (RU 80), have done this for 213 solid and 197 aqueous uranium species. However, their approach has two drawbacks for our analysis: (1) the thermodynamic data for many aqueous species are not known for the transuranic elements we consider most important, and (2) a description of the groundwater chemistry for this type of evaluation requires precise, site-specific concentrations of aqueous species. This type of detailed information is beyond the scope of our generic analysis.

Our approach was to examine the available thermodynamic and solubility data for the important radioactive elements, and select conservative solubility limits (i.e., our reference solubility limits are probably higher than what can reasonably be expected at carefully selected sites). Even so, for most of the solubility-limited radionuclides in Table 4-1, the reference limits are so small that the contribution of these radionuclides to the overall risks is negligible. Even if the solubility limits were an order of magnitude larger, their contribution would still be negligible. An important exception, however, is americium. A large part of the projected risks are attributable to concentrations of americium isotopes. The concentrations of americium in groundwater are usually only limited by solubility constraints in the salt repository backfill, where there is very little water. Thus, determining site specific solubility limits of americium for a salt repository would be a very important step in evaluating the projected risks.

4.3 Geochemical Factors

In the rest of this chapter, we review the information we analyzed to select reference retardation factors and solubility limits for each of the important radionuclides. The solubility limit of americium is one of the more important factors in our risk assessment, and we describe in considerable detail the calculations that we used to select this reference limit.

4.3.1 Americium

4.3.1.1 Solubility

The solubility limit of the americium isotopes is sensitive to the geochemistry of the repository groundwater. To select our reference solubility limit we estimated the solubility of americium in pure water (i.e., zero ionic strength), then we estimated the limit in groundwater with hydroxide, sulfate, chloride, and nitrate complexes. Our analyses indicated that the most conservative approach would be to select the solubility limits for americium hydroxide complexes, since they appear to represent the highest concentration of all species present in solution (i.e., Am^{+3}, $Am^{+3}Cl$, $Am^{+3}OH$).

Americium has two radioactive isotopes of concern, Am-241 and Am-243. Americium is expected to exist in the +3 valence state. According to Rai and Serne (RA 78) the behavior of this ion in pure water is described by the following equilibria equations:

$$Am(OH)_{3_{sol}} \rightleftarrows Am^{+3} + 3OH^- \qquad K_0 = 2.7 \times 10^{-20} \qquad (4\text{-}5)$$

and:

$$Am^{+3}_{aq} \rightleftarrows AmOH^{+2}_{aq} + H^+ \qquad K_1 = 1.2 \times 10^{-6} \qquad (4\text{-}6)$$

K_0 and K_1 are the equilibria constants that describe the thermodynamic relationship of the reactants and products when they have reached equilibrium. The equilibrium constant in equation 4-5 is defined as:

$$\frac{[Am^{+3}]\,[OH^-]^3}{[Am(OH)_3]} = K'_{sol} \qquad (4\text{-}7)$$

where the brackets denote the reacting activity of the species in question.

Since the activity of a solid (e.g., $Am(OH)_3$) at repository conditions is approximately unity, equation 4-7 may be simplified to:

$$[Am^{+3}]\,[OH^-]^3 = K'\,[Am(OH)_3] = 2.7 \times 10^{-20} \qquad (4\text{-}8)$$

If there is no formation of $Am(OH)^{2+}$ or $Am(OH)^+$, then the balance of the masses of the Am^{+3} ion and the hydroxide ion produce three equivalents of OH^- for each equivalent of Am^{+3} species that are in solution. Thus, as a first approximation:

$$[Am^{+3}]\,(3[Am^{+3}])^3 = 2.7 \times 10^{-20} \qquad (4\text{-}9)$$

and solving equation 4-9:

$$27\,[Am^{+3}]^4 = 2.7 \times 10^{-20} \qquad (4\text{-}10)$$

gives:

$$[Am^{+3}] = 5.7 \times 10^{-6}\ m \qquad (4\text{-}11)$$

The limiting concentration of Am^{+3}, using the above assumptions, is 5.7×10^{-6} molar, or approximately 1.4×10^{-3} grams per liter for either Am-241 or Am-243 in pure water of ionic strength zero where the activity coefficient is equal to one and no (OH^-) complexes exist.

According to Rai and Serne (RA 78) and Ames and Rai (AM 78), groundwater may contain hydroxide, nitrate, chloride and sulfate ions. Am^{+3} may form complexes with any of these species. These complexes may be important depending on the concentration of these ions and the formation constants for these complexes. To determine the concentration of the $AmOH^{+2}$ complex in solution due to the dissociation of $Am(OH)_3$, the equilibria for equations 4-5 and 4-6 must be expressed. The equilibrium expression for equation 4-5 has already been shown as equation 4-7. Equilibria for equation 4-6 can be expressed as:

$$\frac{[AmOH^{+2}][H^+]}{[Am^{+3}]} = 1.2 \times 10^{-6} \qquad (4\text{-}12)$$

if the activity coefficient is equal to 1 and the ionic strength is zero. We need to know the equilibrium constant for the following equation:

$$[Am(OH)_3]_{solid} <==> AmOH^{+2}_{aq} + 2OH^- \qquad (4\text{-}13)$$

which can be explicitly stated as:

$$\frac{[AmOH^{+2}]\,[OH^-]^2}{[Am(OH)_3]_{sol}} = K_2 \qquad (4\text{-}14)$$

Multiplication of each side of equation 4-7 by equation 4-12 will yield expression 4-15:

$$\frac{[Am^{+3}]\,[OH^{-}]^{3}\;\;[AmOH^{+2}]\,[H^{+}]}{[Am^{+3}]\,[Am(OH)_{3}]_{sol}} = 2.7 \times 10^{-20} \times 1.2 \times 10^{-6} \tag{4-15}$$

This may be simplified to:

$$\frac{[AmOH^{+2}]\,[OH^{-}]^{3}\,[H^{+}]}{[Am(OH)_{3}]_{sol}} = 3.2 \times 10^{-26} \tag{4-16}$$

When the ionization constant for water is included:

$$[H^{+}]\,[OH^{-}] = 10^{-14} \tag{4-17}$$

equation 4-16 may be further simplified to:

$$\frac{[AmOH^{+2}]\,[OH^{-}]^{2}\,10^{-14}}{[Am(OH)_{3}]_{sol}} = 3.2 \times 10^{-26} \tag{4-18}$$

so that:

$$\frac{[AmOH^{+2}][OH^{-2}]}{[Am(OH)_{3}]_{sol}} = K_{2} = 3.2 \times 10^{-12} \tag{4-19a}$$

$[Am(OH)_{3}]_{sol}$ is defined as 1, thus:

$$K_{2} = [AmOH^{+2}][OH^{-}]^{2} = 3.2 \times 10^{-12} \tag{4-19b}$$

Solving this equation for $[AmOH^{+2}]$ is similar to the solution shown previously for Am^{+3}. This equilibrium concentration of $AmOH^{+2}$ is equal to 9.3×10^{-5} molar or 2.3×10^{-2} grams of americium per liter of water, and a concentration of OH^{-} equal to 1.9×10^{-4} molar.

Since the dissolution of $Am(OH)_3$ to $AmOH^{+2}$ produces a more basic solution than the dissolution of $Am(OH)_3$ to Am^{+3}, these two reactions are competing for a common ion, OH^-. If the acidity of the dissolved solution is calculated using equation 4-17, and OH^- equals 1.9×10^{-4} molar, the concentration of H^+ is 5.3×10^{-11} molar. Using this H^+ concentration, equation 4-12 can be solved for the concentration of Am^{+3}. This solution gives a concentration of 4.1×10^{-9} molar for Am^{+3}, which is much lower than the earlier estimated concentration of Am^{+3}. It is clear that the high stability of $AmOH^{+2}$ results in a lower concentration of Am^{+3}. This Am^{+3} species is important because it can form complexes with chloride, nitrate, and other anions. A low concentration of Am^{+3} will give low concentrations of its complexes.

Rai and Serne (RA 78) indicate that nitrate, chloride, and sulfate may also contribute to complexing. We will discuss the chloride complex since this is the more common of the three complexes for the groundwater of interest. For chloride calculations a 10 molar solution of NaCl is used, although this concentration slightly exceeds the solubility of NaCl. For the reaction:

$$Am^{+3} + Cl^- \rightleftharpoons AmCl^{+2}, \qquad (4\text{-}20)$$

Rai and Serne (RA 78) indicate:

$$\frac{[AmCl^{+2}]}{[Am^{+3}]\,[Cl^{-}]} = 1.5 \times 10^{1} = K_3 \qquad (4\text{-}21)$$

Since we assume the chloride concentration is 10 molar, the ratio of the complex $AmCl^{+2}$ to the uncomplexed ion will be:

$$\frac{[AmCl^{+2}]}{[Am^{+3}]} = 150 \qquad (4\text{-}22)$$

For the Am^{+3} concentration of 4.1×10^{-9} molar, the concentration of the complex $AmCl^{+2}$ is 6.2×10^{-7} molar or 1.5×10^{-4} grams/liter. The concentration of the hydroxyl complex is over 100 times higher than the concentration of the chloride complex. Thus, supported by the work of Ames and Rai (AM 78) and Rai and Serne (RA 78), we estimate that the most significant species in the dissolution of $Am(OH)_3$ is the monohydroxo $(AmOH)^{+2}$ complex. Since we calculated the concentration of this complex to be 2.3×10^{-2} grams/liter, we chose a conservative limiting solubility of 5.0×10^{-2} grams/liter for this study. This allows for some reasonable uncertainties in the equilibrium constants as well as for those complexes for which no equilibrium constants have been measured. This limiting solubility is equivalent to 160 curies/m^3 for Am-241 and 10 curies/m^3 for Am-243. Recent work by Rai and Strickert (RA 80) and Ogard, et al. (OG 80) and Rai, et al. (RA 81) suggest that americium is much less soluble than these concentrations. The most recent work by Rai, et al. (RA 81) suggests that americium solubility limits are 100 to 100,000 times lower than the values used in our analyses. These workers have not, however, identified the species responsible for this lower solubility.

4.3.1.2 Retardation Factors

In their recent review of the literature on radionuclide interactions with soils and rocks, Ames and Rai (AM 78) observe that the K_d for americium ranges from 0 to 50,000 milliliters per gram. We have selected a reference retardation factor for americium of 100 for this report. Many of the low K_d values--and, consequently, retardation factors--summarized by Ames and Rai (AM 78) are for solutions with high concentrations of organic compounds. We think that repositories can be found where the groundwater does not have a high concentration of organic compounds. Therefore, we believe a retardation factor of 100 is clearly achievable.

4.3.2 Carbon

Carbon exists in spent fuel as C-14, an activation product whose chemical form is unknown. For this reason we have assumed there is no limiting solubility for C-14 and that any C-14 that migrates does so with a retardation factor of one.

4.3.3 Cesium

Ames and Rai (AM 78) indicate cesium is highly soluble, therefore we have not used a solubility limit. They also report measured Kd values ranging from 0 to almost 100,000 for different rocks and minerals. Because of the wide variation in the reported values, the reference case retardation factor is one.

4.3.4 Iodine

According to Ames and Rai (AM 78), I-129 usually exists as iodide, which is very soluble. For this reason no limiting solubility has been used. Since iodide is anionic, we can expect little or no retention in soil. Thus we have chosen a retardation factor of one, which is the same retardation factor reported by Denham, et al. (DE 73).

4.3.5 Neptunium

Neptunium-237 is produced in a reactor primarily by activation of uranium. Np-237 will exist in either a +4 or +5 valence state in most natural conditions (PO 66, BO 79, AM 78). In a neutral or basic environment with reducing conditions, the +4 valence state will predominate (BO 79, PO 66).

4.3.5.1 Solubility

In a reducing environment, the expected chemical state of Np-237 is tetravalent. Bondietti and Francis (BO 79) placed a 16 nM (3.8 parts per billion) solution of Np-237 in contact with a number of different rock types and measured a substantial loss of Np from their solution. They identify this behavior as a reduction of NpO_2^+ to the relatively insoluble NpO_2 species. This reduction is confirmed by Ames and Rai (AM 78). They indicate that the +4 species of Np is very insoluble. Hence, we use a solubility limit of one part per billion in water for neptunium, which is equivalent to a solubility limit of 7.2×10^{-7} curies/m^3.

4.3.5.2 Retardation Factors

A wide range of retardation factors has been reported for neptunium (AM 78, BO 79). However, Bondietti and Francis are the only investigators who have examined the geochemical relationship between neptunium and the oxidation potential of the host rock. We have selected a retardation factor of 100, which is the same factor reported by Denham, et al. (DE 73). Some measurements have shown that the retardation factor of neptunium can be lower than 100, but these measurements were made under geochemical environments that were not representative of good repository conditions.

4.3.6 Plutonium

Plutonium exists in spent fuel as a mixture of plutonium-238, -239, -240, -241, and -242. Chemically, plutonium exists in the +3, +4, +5, and +6 valence states. A number of papers review the stability and migration of plutonium and its compounds (AM 78, RA 77, RA 78, PO 66).

4.3.6.1 Solubility

All of the reviews indicate that plutonium is very insoluble in a basic reducing environment. We use a solubility limit of one part per billion for plutonium, even though concentrations shown in the reports cited are sometimes much lower. We believe the plutonium will be present as a tetravalent solid. This solubility limit corresponds to limits for plutonium-238, -239, -240, and -242 of 1.7×10^{-2}, 6×10^{-5}, 2×10^{-4} and 4×10^{-6} curies/m^3, respectively.

4.3.6.2 Retardation Factors

Ames and Rai (AM 78) indicate an extremely wide range of retardation factors for Pu. Most of the low K_d values summarized by Ames and Rai are for solutions with high organic content. We use a retardation factor of 100, which is substantially below that measured by most workers and is much less than the 10,000 reported by Denham, et al. (DE 73).

4.3.7 Strontium

Strontium-90 is a fission product which exists as a +2 cation in rock, and its salts are moderately soluble (AM 78). For this reason we have used no solubility limit in this report. A wide range of retardation factors has been reported for Sr-90. In this report we use a retardation factor of one, which clearly underestimates the extent of retention we expect for migrating strontium (AM 78).

4.3.8 Technetium

Technetium-99 is a fission product that exists in many chemical states from +7 to -1. The most stable valence states are the +7 and +4 (PO 66, AM 78, BO 79). The +7 form is highly soluble and mobile, and the +4 form is virtually insoluble and immobile. Under the reducing geochemical environment that is favorable for repository siting, we believe the less soluble and mobile +4 form will be the most common.

4.3.8.1 Solubility

Using the solubility data of Pourbaix (PO 66) and Bondietti and Francis (BO 79), we predict a low concentration of Tc in reducing groundwater. Bondietti and Francis observed a substantial loss (over 95 percent) of Tc from a 0.11 μM (11 ppb) solution after contact with reducing rocks. Based on this experiment and associated stability information, we have chosen a solubility limit of one part per billion, which is equivalent to 2 x 10^{-5} curies/m^3.

4.3.8.2 Retardation Factor

A retardation factor of one has been selected for Tc-99. The review of Ames and Rai (AM 78) and work of Bondietti and Francis (BO 79) makes it clear that Tc-99 is mobile under some circumstances, even when it is at low concentrations. Since the measurements are ambiguous, the conservative approach is to assume the lowest reasonable retardation factor, which in this case is one. It is also likely that any technetium in solution would be the mobile +7 form rather than the insoluble, immobile +4 oxide.

4.3.9 Tin

Tin-126 has received little attention as a nuclear fission product. Neither the reviews of Ames and Rai (AM 78), or Rai and Serne (RA 78) discuss this isotope at all, and it appears that little or no work has been done concerning it.

4.3.9.1 Solubility

Pourbaix (PO 66) reports that, excluding complexation, SnO is the most soluble form of tin. The other form is SnO_2, which is less soluble and would exist in oxidizing environments rather than in reducing environments. According to Pourbaix (PO 66):

$$\log (Sn^{+2}) = 1.07 - 2pH \quad (4\text{-}23)$$

and:

$$\log (HSnO_2^-) = -14.81 + pH. \quad (4\text{-}24)$$

For a pH = 7 these equations can be solved to be:

$$(Sn^{+2}) = {\sim}10^{-13} \quad (4\text{-}25)$$

and:

$$(HSnO_2^-) = {\sim}10^{-7} \quad (4\text{-}26)$$

Sillen and Martell (SI 64) report strong chloride complexes with Sn^{+2}. These complexes should be less than the $HSnO_2^-$ ion concentration unless the equilibrium constants summarized by Sillen and Martell are substantially in error. They report no simple complexes of $HSnO_2^-$. To maintain a conservative solubility limit for tin, we selected a limit of one part per million, or 3×10^{-2} curies/m^3. This concentration may overestimate the solubility of tin by a considerable margin.

4.3.9.2 Retardation Factor

Tin should exist predominantly as an anion, even though it can exist as a cation. Tin should be relatively mobile compared to the actinides, which are cationic. However since it can exist as a cation, we have selected a retardation factor of 10 instead of 1. Clearly, further experimental work is needed to determine the retardation factor.

4.3.10 Uranium

Although this report does not consider the health impact of uranium in spent fuel, it is possible that the solubility of uranium could limit the rate at which most nuclides are leached into repository groundwater. While some waste nuclides would not be trapped in the UO_2 matrix (I or Cs, for example), other nuclides (Np, Pu or Am, for example) would subsitute for uranium in the uranium dioxide matrix. For reprocessed high-level waste, the uranium would be separated by a chemical process, and the release of waste nuclides to water would not be dependent on the solubility of uranium. Ogard, et al. (OG 80) consider the effects of uranium solubility on leaching rates in a mildly reducing environment.

Ames and Rai (AM 78), Langmuir (LA 78), and Rai and Serne (RA 78) discuss the solubility of uranium and its compounds. Based upon their stability diagrams, we chose a solubility limit of one part per billion. This concentration is at the lower end of values given by Fix (FI 55) and Germanov and Panteleyev (GE 68) for the uraniferous waters they examined.

4.3.11 Zirconium

Zirconium exists in waste in a +4 valence state. It is one of the most insoluble and geochemically immobile elements.

4.3.11.1 Solubility

Ames and Rai (AM 78) show the solubility of solid ZrO_2 and $Zr(OH)_4$ to be very low. We have taken the solubility for zirconium to be one part per billion. This estimate is well in excess of values shown graphically in Figure 3-28 of Ames and Rai's work. This solubility is equivalent to 2.6×10^{-6} curies/m^3.

4.3.11.2 Retardation Factor

Zirconium is strongly sorbed, and the review by Ames and Rai (AM 78) shows both experimental and field data in complete agreement on this point. For the reference retardation factor, we used a conservative value of 100. The distribution coefficients summarized by Ames and Pai (AM 78) are consistently higher than 100.

Chapter 5 - RELEASE MECHANISMS AND PROBABILITIES

This chapter presents models to describe the release of radionuclides to the environment from various unplanned release mechanisms and from normal groundwater flow. Our models and assumptions are based on information in the ADL report (ADL 79d). First, general models are developed to describe the movement of radionuclides either released directly to the air or land surface or released by transport in groundwater to an aquifer. Then, the general models are expanded in order to describe specific release mechanisms and normal groundwater flow in various repository media. Where possible, model parameter values are suggested for use in evaluating the impact of various release mechanisms on the environment. Summary tables of the parameters introduced in this chapter are also displayed with the probability and consequence evaluations in Chapter 7. Techniques for solving the equations presented in this chapter are described in Appendix C.

5.1 General Release Models

Releases of radioactivity from a repository can be the result of a direct physical disturbance of the waste package or an indirect disturbance caused by disruption of the repository containing the waste. Direct disturbances can result in transport of a fraction of the waste to the land surface or into the air, followed by release of the waste remaining in the repository to groundwater and then to an overlying aquifer.

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Mechanisms of direct waste package disturbance include the following:

Mechanism	Results in release to
Volcanoes	air and land surface
Meteorites	air and land surface
Drilling	land surface and aquifer
Faulting	aquifer
Breccia pipes	aquifer

Disruption of the repository can result in indirect disturbance of the waste package, allowing the release of radioactivity to either the land surface or transport in groundwater to an aquifer. Repository disruption mechanisms that might lead to the release of radioactivity include the following:

Mechanism	Results in release to
Drilling	land surface and aquifer
Faulting	aquifer
Breccia pipes	aquifer

5.1.1 Direct Impact: Releases to Air and Land Surface

The model equation we have used to calculate direct releases to the land surface or into the air is:

$$Q = fQ_o e^{-\lambda t_e} \tag{5-1}$$

where:

Q = activity of released waste, curies
f = fraction of repository inventory released
Q_o = initial radionuclide inventory, curies
λ = radionuclide decay constant, yr^{-1}
t_e = time event occurred after repository sealing, years.

The exponential term, $e^{-\lambda t_e}$, reduces the initial radionuclide inventory of the repository by the amount of radioactive decay of the radionuclide since repository sealing.

5.1.2 Direct Impact: Release to an Aquifer

After disturbance of the waste package causes release of some radioactivity, the radioactivity remaining in the waste package may be transported to the overlying aquifer by diffusion and convective flow. ADL discusses the diffusion process and concludes that transport by diffusion is usually much slower than transport by convective flow (ADL 79d). Transport by convective flow depends on the radionuclide release rate from the waste matrix, the solubility of the radionuclide in water, and the radionuclide inventory at the time of interest. If there are no limits to radionuclide solubility, the equation for the radionuclide release rate into the groundwater in the repository is:

$$\begin{aligned} \dot{Q} &= 0 && t<t_e \\ \dot{Q} &= LfQ_0 e^{-\lambda t}\, e^{-L(t-t_e)} && t>t_e \end{aligned} \qquad (5\text{-}2a)$$

where:

$\dot{Q}$ = release rate from the waste, Ci/yr
L = fractional release rate from the waste matrix, yr^{-1}
f = fraction of waste impacted
t = time of interest
t_e = time of event

If the radionuclide is solubility limited, the release rate from the waste matrix is the product of the solubility limit and the volumetric flow of water. Equation 5-2b is the expression of this release rate:

$$\dot{Q} = C_o V^*(t) \tag{5-2b}$$

where:

C_o = solubility limit, Ci/m^3

$V^*(t)$ = volumetric flow rate from the repository to the overlying aquifer, m^3/yr.

The volumetric flow rates are different for each of the host repositories. Equations describing $V^*(t)$ are presented in Section 5.2.1. The total quantity of a radionuclide released from the time of the direct disturbance to the time of interest is the integral of equation 5-2a or 5-2b over that time period.

5.1.3 Repository Disruptions: Releases to Land Surface

Events which do not directly disturb the waste package but do disrupt the surrounding repository require more complicated equations to describe releases to the land surface or to the overlying aquifer. The pore spaces of a repository will become saturated with water which begins migrating into the repository as soon as it is sealed. When the canisters fail, the waste matrix will begin to dissolve. As the waste matrix dissolves, a slow buildup of radioactivity occurs in the pore volume of the repository. This radioactivity can be transported to the overlying aquifer or to the land surface if the repository is disturbed. Releases from the pore volume can be modeled by developing an equation that balances the inputs and outputs of radioactivity in the pore spaces.

The rate of change of the activity in the pore volume can be expressed as the product of the volume of pores, V, and the derivative of the concentration of radionuclides over time, dC(t)/dt. This product is equal to the sum of the input of radionuclides into the pores by leaching from the waste, $LfQ_c(t)$, and the output of radioactivity by radioactive decay, $-\lambda VC(t)$. The resultant expression for the rate of change of activity is:

$$V \frac{dC(t)}{dt} = LfQ_c(t) - \lambda VC(t) \qquad (5\text{-}3a)$$

where:

$$Q_c(t) = Q_o e^{-\lambda t} e^{-L(t-t_c)} \qquad (5\text{-}3b)$$

and:

V = pore volume, m^3
C(t) = activity/volume = concentration in V, Ci/m^3
$Q_c(t)$ = activity in affected waste, curies
f = fraction of waste leaching into void volume V
t_c = lifetime of the canister shell, years.

The activity of the waste, $Q_c(t)$, remaining in the repository is the product of the inventory of radionuclides, Q_o, the rate of radioactive decay up to the time of interest, $e^{-\lambda t_i}$, and the rate of release--which only takes place from the time of canister failure, t_c, until the time of interest t, [$e^{-L(t-t_c)}$ where $t > t_c$]--as shown by equation 5-3b. We have made the worst-case assumption of simultaneous failure of all canisters, and equation 5-3a models the sum of all canisters of waste rather than failure of an individual canister. Each factor in equation 5-3a thus involves the sum of all canisters (i.e., Q_o = inventory of the sum of the waste in all canisters). The solution to equation 5-3a is obtained by substituting 5-3b into 5-3a and assuming that the concentration, C(t), is zero up until the time of canister failure (until $t = t_c$). This yields:

$$C(t) = fQ_o e^{-\lambda t}[1-e^{-L(t-t_c)}]/V \tag{5-4}$$

where:

all of the variables are as defined for equation 5-3.

The solution of equation (5-3a) is described in detail in Appendix C. If the radionuclide is solubility limited, C(t) is replaced by the solubility limit, C_o.

5.1.4 Repository Disruptions: Releases to an Aquifer

The differential equation describing the change in activity in the pore volume during release to an overlying aquifer is identical to equation 5-3a--with the addition of a term to account for the removal of radioactivity from the repository by ground water flow, V*(t) C(t). The resulting equation is:

$$V \frac{dC(t)}{dt} = LfQ_c(t) - \lambda VC(t) - V^*(t)C(t) \tag{5-5}$$

where:

$V^*(t)$ = volumetric flow rate, m^3/yr.

All the remaining variables are as defined for equation 5-3a.

This equation is solved using an integrating factor in a manner similar to that used to solve equation 5-3a [see Appendix C (C.2)]. The general form of the solution is:

$$C(t) = \frac{1}{\mu(t)} \int_{t_e}^{t} \mu(s)q(s)ds + \frac{C(t_e)\mu(t_e)}{\mu(t)} \qquad (5\text{-}6)$$

where:

t = time of interest, years

t_e = initial time of release, years

t_c = lifetime of canister, years

$\mu(s)$ = $EXP[\int^{s} [\lambda + V^*(s)/V]\, ds]$

$q(s)$ = $(LfQ_0/V)\ EXP(-\lambda s - Ls + Lt_c)$

$C(t_e)$ = concentration at the initial time of release (see equation 5-4 for $t=t_e$).

Equations describing $V^*(t)$ for the various materials of the surrounding repository are presented in section 5.2.1. A solution to equation 5-5 using $V^*(t)$ as defined by equation 5-20 is presented in Appendix C.

Some release events have very large calculated groundwater flow rates from the repository to the overlying aquifer. If these calculated flow rates are faster than the rate of recharge of groundwater to the repository, we assume the flow rates are limited by the rate of flow of water from the underlying aquifer. In these cases, $V^*(t)$ in equation 5-5 is a constant, V_{aq}. By substituting V_{aq} for $V^*(t)$ in equation 5-5, the rate of change of activity can be expressed:

$$\frac{VdC(t)}{dt} = LfQ_c(t) - \lambda VC(t) - V_{aq}C(t) \qquad (5\text{-}7)$$

The solution is an integral of the form of equation 5-6 evaluated from the time of the event to the time of interest. The solution is presented in Appendix C (C.3). If the radionuclide is solubility limited, C(t) is replaced with the solubility limit, C_o, expressed in Ci/m^3.

The product of the concentration and volumetric flow rate in equations 5-4 and 5-5 is the rate of radionuclide released to the aquifer over time. The total release to the aquifer is the integral of this product from the time of the event to the time of interest, t_i:

$$Q = \int_{t_e}^{t_i} C(t)\ V^{*}(t)\ dt \qquad (5\text{-}8)$$

5.2 Specific Release Mechanisms

This section is arranged according to the following release mechanisms: normal groundwater flow, human intrusion (drilling), faulting, breccia pipe formation, meteorites, and volcanoes. Mathematical equations are used to calculate concentrations of radionuclides at the time of release and within pathways following release. Parameters are introduced for solution of the equations for repositories in various rock types. A complete discussion of the initiating events and their effects on a repository is contained in Volume D of ADL's report (ADL 79d).

The release pathways for each release mechanism are listed below:

Mechanism	Pathway
Normal Groundwater Flow	surface water via aquifer
Human Intrusion	land surface and surface water via aquifer
Faulting	surface water via aquifer
Breccia pipes	surface water via aquifer
Meteorites	air and land surface
Volcanoes	air and land surface

5.2.1 Normal Groundwater Flow

5.2.1.1 Salt Repositories

Release by normal groundwater flow at a salt repository is governed by the interaction of two processes. Water may be recharging the voids in the repository backfill while lithostatic pressure is simultaneously reducing the volume of the voids. If the volume reduction exceeds the initial volume of unsaturated voids, contaminated water may be squeezed out of the backfill and into the overlying aquifer. Equations for water flow, rate of repository closure, and maximum and minimum pore volume (developed in chapter 3) are used to estimate the potential volume of contaminated water. Equations for radionuclide concentration are then applied in order to describe possible releases of radionuclides.

The lithostatic pressure of the overburden causes the salt to deform plastically, thereby reducing the void volume and fully sealing the repository within a few hundred to a thousand years. After the repository seals itself, the salt is essentially impermeable to water flow and further releases of radioactivity are not expected. Before closure is complete, however, degradation of the shafts (section 2.3) can allow some water to flow down into the unsaturated backfill. Recharge water that fills the voids of the backfill may be squeezed back up these shafts owing to the lithostatic pressure acting to seal the repository. Determining the volume of this water is important in estimating the degree of contamination by normal groundwater flow out of a salt repository.

The volumetric flow of water from an overlying aquifer through the permeable shaft can be calculated using Darcy's Law (equation 3-9), $V^*(t) = KiAc(\mu)$. The parameters substituted in this equation are:

$V^*(t)$ = time dependent flow rate of water from the overlying aquifer into the pores of the repository backfill, m^3/yr.

$K = K_0 + K't$ linearly increasing hydraulic conductivity of the shaft seals (section 2.3) m/yr

i = hydraulic gradient between the overlying aquifer and the repository.

A = area of the shafts, m^2.

$c(\mu)$ = viscosity correction factor (section 3.2)

Substitution for K results in:

$$V^*(t) = (K_0 + K't)\, c(\mu)\, i\, A \qquad (5\text{-}9)$$

The coefficient of hydraulic conductivity of the shafts ($K_o + K't$) was developed by ADL (ADL 79d) assuming an initial shaft seal hydraulic conductivity, K_o, of 3.2×10^{-3} m/yr. Since better information is not available, the shaft seals are assumed to degrade linearly over 10,000 years (t_1) to increased hydraulic conductivity values (K_1) of 0.32 m/yr for main shafts and 3.2 m/yr for the miscellaneous boreholes. These values are representative of the range of hydraulic conductivity for sand or silt. Our estimate of K' is:

$$K' = (K_1 - K_o)/t_1 = 3.17 \times 10^{-5}$$

resulting in:

$$K = (3.2 \times 10^{-3} + 3.17 \times 10^{-5}t) \text{ m/yr.}$$

In order to calculate the hydraulic gradient between the overlying aquifer and the repository, we assume that there is no resistance to vertical flow within the aquifer and that all head loss occurs between the repository and the bottom of the aquifer. The hydraulic head at the top of the aquifer (130 meters above the repository in the bedded salt example) is then essentially equal to that at the bottom of the aquifer (100 meters above the repository). The head difference between the repository and the bottom of the aquifer (130m) is divided by the path length (100m) for a hydraulic gradient of 130/100 = 1.3. For a domed salt repository, the respective parameters yield a hydraulic gradient of 260/230 = 1.1.

The area of the main shafts (4 shafts 5m x 5m each) is calculated to be 100 m^2 (ADL 79d). Each borehole is assumed to have a cross-sectional area of 0.1 m^2. There are assumed to be 50 boreholes from the upper aquifer to the repository in both bedded salt and domed salt. In addition, the bedded salt repository is assumed to have 10 boreholes extending to the lower aquifer for a total of 60 boreholes. The total shaft area is thus:

Bedded salt: $A = 100m^2 + .1m^2(60) = 106m^2$.

Domed salt: $A = 100m^2 + .1m^2(50) = 105m^2$.

The viscosity correction factor, $c(\mu)$, for our analyses is 5 and is based on a water viscosity, μ, of 0.002 poise at a temperature of 125°C.

Substituting all of these parameters into equation 5-9 yields a flow rate of water through shaft seals into bedded salt and domed salt repositories of:

Bedded salt repository: $V^*(t) = 2.2 + 0.021t$ (5-10)

Domed salt repository: $V^*(t) = 1.8 + 0.018t$ (5-11)

The total volume of water which can flow into each repository through all of these pathways is the integral of each of these equations over the time it takes for the decreasing pore volume of the repository backfill to equal the volume of the water that has leaked in to fill the pores (saturation time).

An expression has been developed to describe the maximum volume of recharge water--but, in order to evaluate this integral, the time at which the volume of water equals the pore volume (saturation time) must be evaluated. This is done by setting the expression for the volume of water equal to the expression for the remaining volume of the voids and solving them simultaneously. The initial volume of the voids, V_o, is 2×10^6 m^3 (section 2.3). The sealing of the repository by salt creep is anticipated to collapse pore spaces in the backfill down to a minimum void volume, V_{min}, of 20,000 m^3--or down to the amount of water that has entered through the shaft and borehole seals if the amount is less than 20,000 m^3 by the time of repository closure, T_{clos}. If more than 20,000 m^3 of water has entered by the time of closure, the amount in excess of 20,000 m^3 is assumed to be squeezed back up the shafts, as described in the following paragraphs. T_{clos}, the time required for reduction of the void volume, is assumed to be 200 years (ADL 79d). The expression for pore volume, V_v, at time t is thus:

$$V_v = V_{min} + (V_o - V_{min})\,(T_{clos} - t)/T_{clos} \qquad (5\text{-}12)$$

where:

V_v = volume of the voids at time t, m^3
V_o = initial volume of the voids, m^3
V_{min} = minimum volume of the voids, m^3
T_{clos} = time of closure, years.

Using the example for bedded salt, the integral of the flow rate in equation 5-10 is set equal to the void volume of 5-12:

$$V_{min} + (V_o - V_{min})(T_{clos} - t)/T_{clos} = 2.2 + 0.021t \qquad (5\text{-}13a)$$

Substituting $V_o = 2 \times 10^6\ m^3$, $V_{min} = 2 \times 10^4\ m^3$, and $T_{clos} = 200$ years and integrating yields:

$$(2 \times 10^4) + (2 \times 10^6 - 2 \times 10^4)(200 - t)/200 = 2.2t + 0.0105t^2 \qquad (5\text{-}13b)$$

The solution for t in this expression is always negative. This means that the volume of water leaking into the repository does not equal or exceed the minimum pore volume within the 200 year assumed closure time. This can be verified by calculating the water volume after 200 years by substituting 200 for t in the right-hand side of equation 5-13b. This substitution yields a water inflow volume of 878 m^3 after 200 years. Since the volume of water in the voids does not exceed V_{min}, no water would be squeezed back out of the backfill in this example. The estimate for the amount of water that leaks into a salt repository by T_{clos} (878 m^3 in this case) is used in section 5.2.2.1 to calculate the amount of contaminated water that might be brought to the land surface by inadvertant human intrusion.

If different parameters were selected for a more conservative analysis--or for a different case such that the hydraulic conductivity, K, for the shafts and boreholes was larger or the closure time, T_{clos}, was assumed to be longer (ADL 79d, second estimate), then more than 20,000 m^3 of water could flow into the backfill in less time than the closure period. The repository closure time would be longer than the saturation time.

The remaining void volume would be less than the water inflow volume and the excess water (which may be contaminated) could be squeezed back up the shafts and boreholes. The volume of water remaining in the repository after the lithostatic pressure begins to squeeze water up the shafts and boreholes can be calculated using the following equation:

$$V(t) = V_{rch} - \int_{T_{rch}}^{t} V^{*}(s)\, ds \qquad (5\text{-}14a)$$

where:

$V(t)$ = the time dependent saturated repository volume, m^3

V_{rch} = the volume of water when the backfill of the repository is initially saturated, m^3

T_{rch} = the time when recharging is complete, years.

and the rate of water flowing back up the boreholes is:

$$V^{*}(t) = K(t)\ i\ A\ c(\mu) \qquad (5\text{-}14b)$$

with:

$K(t) = K_0 + K' t$ (equation 5-9)

A = area of the shafts

i = hydraulic gradient caused by the change in lithostatic pressure (described below)

$c(\mu)$ = viscosity correction factor

To evaluate equation 5-14a and 5-14b, we used the same coefficient of hydraulic conductivity, K, and the same shaft area that were used to evaluate equations 5-10 (bedded salt) and 5-11 (domed salt). The effective hydraulic gradient generated by salt creep may be estimated as follows. The pressure exerted by the salt on the pore water is roughly equal to (and certainly bounded by) lithostatic pressure, which--assuming a rock density twice that of water--can be approximated by twice the hydrostatic pressure of a column of water extending to the surface. For bedded salt with a repository whose depth is 460 meters, this corresponds to a pressure head of 920 meters of water. The saturated permeable shafts cover a distance of 100 meters from the repository to the bottom of the aquifer, at which point the hydrostatic pressure is approximately 30 meters of water. Therefore, a net head difference of 920-100-30 = 790 meters of water acts over a path length of 100 meters, corresponding to a maximum hydraulic gradient of $i = 790/100 = 7.9$. Because this number overestimates the driving force, it is slightly conservative and appropriate for the approach of this report. The value is conservative because full lithostatic pressure on the pore water will never quite be achieved as long as there is a flow path from the repository. The volume of water which flows into the repository, V_{rch}, and the time required for saturation, T_{rch}, can be calculated using equation 5-13a.

The rate of volumetric change of the repository after resaturation cannot be greater than the closure rate before resaturation. The flow rate of water calculated from equation 5-14b must be checked with the volume reduction calculated by equation 5-12. If the water flow rate predicted by 5-14b is faster than the volume reduction rate, then the slower rate must logically be assumed. To make this comparison of the two methods, we will rewrite equation 5-12 into terms that correspond to the terms in equation 5-14a and 5-14b.

Equation 5-12 can be simplified slightly by expanding terms, resulting in:

$$V(t) = V_o + (V_{min} - V_o)\ t/T_{clos} \qquad (5\text{-}15a)$$

The rate of volumetric change, $V^*(t)$, is assumed to be a linear function changing from the initial pore volume, V_o, to the minimum pore volume, V_{min}, over the closure time, T_{clos}:

$$V^*(t) = (V_o - V_{min})/T_{clos} \qquad (5\text{-}15b)$$

In both sets of equations (5-14a and b, and 5-15a and b) $V^*(t)$ is equal to $-d(V(t))/dt$. The smaller of the volumetric rates (5-14b or 5-15b) should be used as the basis for selecting the proper volume and volumetric rates for predicting concentrations of radionuclides in forthcoming equations.

During the time it takes to saturate the repository and the time it takes to force the water back up the shafts due to the effects of lithostatic pressure, radionuclides may be released from the canisters into the water in the backfill. The change in activity of radionuclides over time--assuming the entire repository is affected equally (f=1)--can be calculated using the expression:.

$$\frac{dQ(t)}{dt} = L\ Q_c(t) - \lambda Q(t) - V^*(t)\ Q(t)/V(t) \qquad (5\text{-}16)$$

where:

$V^*(t)$ = the volumetric flow rate back up the shafts, m^3/yr

$V(t)$ = the time dependent volume of water in the repository, m^3

$Q(t) = C(t)\ V(t)$

and the other variables are as defined for equation 5-3a.

Substituting C(t)V(t) for Q(t) yields:

$$V(t)\,\frac{dC(t)}{dt} + C(t)\,\frac{dV(t)}{dt} = LQ_c(t) - \lambda C(t)V(t) - V^*(t)C(t) \qquad (5\text{-}17)$$

Substituting -V*(t) for d(V(t))/dt--from the relationships between equations 5-14a and b, and between 5-15a and b--and factoring V(t) yields:

$$\frac{dC(t)}{dt} = LQ_c(t)/V(t) - \lambda C(t) \qquad (5\text{-}18)$$

Equation 5-18 is of the form [p(s)y + y' = q(s)] and can solved in the same manner as equations 5-3a and 5-5. The solution is of the form of equation 5-6 with:

$\mu(t) = e^{\lambda t}$

$q(t) = L\, Q_c(t)/V^*(t)$

$C(te) = C(T_{rch})$

T_{rch} = saturation time

Using equation 5-4, the concentration of radioactivity at saturation time can be evaluated as:

$$C(T_{rch}) = Q_o\, e^{-\lambda T_{rch}}\, [1 - e^{-L(T_{rch}-t_c)}]\, /V_{rch} \qquad (5\text{-}19)$$

where:

V_{rch} = the volume of water at initial saturation time.

This solution is described in Appendix C (C.4). The rate of release of radionuclides is the product of the radionuclide concentration and the volumetric flow of water. The cumulative radionuclide release is the integral of this product (equation 5-8) evaluated, for this case, from time of initial saturation, T_{rcn}, to the time of repository closure, T_{clos}. If the radionuclide is solubility limited, C(t) is replaced by the solubility limit, C_o. A summary of the parameters used to evaluate releases from salt repositories caused by resaturation of repository backfill and the effects of salt creep are summarized in Table 7-2.

5.2.1.2 Granite, Shale, Basalt Repositories

Groundwater flow through the host rock of a repository can be altered by the effects of the heat produced during radioactive decay. Temperature changes will cause stress changes in the host rock that may alter the hydraulic properties of that rock through such processes as: rock expansion, compaction of fill, slippage and movement along fractures, and mineral alteration. In the immediate vicinity of the waste, temperatures as high as 100-200 degrees centigrade are predicted (ADL 79d). The temperature rise may actually cause a decrease in rock permeability, thereby restricting flow; however, the subsequent temperature decrease may result in increased permeability and increased water flow.

To analyze the effects of temperature change on the volumetric flow of water through the host rock, we used another application of Darcy's law:

$$V^*(t) = KAi(t)c(\mu) \qquad (5\text{-}20)$$

where all the parameters are as defined for equation 5-9. The hydraulic gradient, i(t), and the viscosity correction factor, $c(\mu)$, both change over time because of the alteration processes caused by the temperature changes. The changes in these two parameters were calculated independently by ADL (ADL 79d) for each repository host rock. The general equation describing changes in hydraulic gradient and viscosity over time is:

$$i(t)c(\mu) = ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a \qquad (5\text{-}21)$$

The parameters a, b, c, α, β and γ and i_a vary with rock type when this expression is used to evaluate equation 5-20.

The effects of waste heat on the host rock matrix may alter its fluid transmitting properties such that the hydraulic conductivity is increased by a factor of 10. If so, representative values of hydraulic conductivity would be 3×10^{-4} m/yr for granite and 3×10^{-3} m/yr for basalt and shale. The cross-sectional area (A in equation 5-20) of the repository is 8km^2. The values used as input for the flow through bulk rock calculations are summarized in Table 7-2.

The build-up of the radionuclide concentration in the repository groundwater, C(t), is estimated by solving equation 5-5 using the volumetric flow V*(t) described by equation 5-20. The solution is presented in Appendix C (C.5). In this case, f=1, and the solution has the general form of equation 5-6, with the following parameters:

$$q(t) = \frac{L}{V} Q_C(t)$$

$$p(t) = \lambda + K\ A\ i(t)\ c(\mu)\ /\ V$$

$C(t_C) = 0$ at the time of failure of the canisters

If the calculated volumetric flow rate of water $V^*(t)$ exceeds the limiting aquifer flow, V_{aq}, then equation 5-5 is solved using V_{aq} in place of $V^*(t)$. This is the same as solving equation 5-7 with f=1:

$$V \frac{dC(t)}{dt} = LQ_c(t) - \lambda VC(t) - V_{aq}\, C(t) \qquad (5\text{-}22)$$

The radionuclide concentration, C(t), is determined by solving this equation in the same manner as equation 5-7 is solved in Appendix C (C.3). The integral is solved from time = t_c to the time of interest, which yields the following expression for C(t):

$$C(t) = \frac{LQ_o\, e^{-(\lambda+V_{aq}/V)t}\, e^{(L\ t_c)}}{V_{aq} - V\ L} \left[e^{-(L-V_{aq}/V)t} - e^{-(L-V_{aq}/V)t_c} \right] \qquad (5\text{-}23)$$

If the radionuclide is solubility limited, the concentration, C(t), in the repository voids is assumed to equal the solubility limit, C_o.

To calculate releases from the repositories, the product of the concentration and volumetric flow rate is integrated from the time of canister failure, t_c, until the time of interest, t_i. The following equations illustrate this integral:

No aquifer flow limit or solubilitiy limit:

$$Q = \int_{t_c}^{t_i} V(t)\ C(t)dt \tag{5-24}$$

Aquifer flow limit, no solubility limit:

$$Q = V_{aq} \int_{t_c}^{t_i} C(t)dt \tag{5-25}$$

Solubility limit, no aquifer flow limit:

$$Q = C_o \int_{t_c}^{t_i} V(t)dt \tag{5-26}$$

Limits on both aquifer flow and solubility:

$$Q = V_{aq}\ C_o\ (t_i - t_c) \tag{5-27}$$

Some of these integrals cannot be solved analytically and must be evaluated numerically.

5.2.2 Human Intrusion (Drilling)

Future drilling at a repository site might either directly impact waste or disturb the host rock surrounding the waste. The worst result would be a direct deposition of radioactive material on the land surface overlying the repository. Analysis of a quantitative model for human intrusion indicates the most important aspects would be the frequency of drilling, the quantity of material transported to the surface, and the assumptions made about remedial actions taken after a release.

We have assumed that institutional controls will prevent any human intrusion for the first 100 years, after which time we assume the site will revert to prevailing land use patterns. Based on these assumptions ADL estimated the frequency of future drilling. Table 7-3 details the annual probabilities of drilling into each type of repository. The drilling activities we have considered for each repository type are:

1. oil and gas exploration
2. water exploration
3. geothermal resources evaluation
4. brine injection or disposal of other wastes
5. mineral exploration
6. scientific investigation
7. fluid storage

Past drilling rates into potential repository formations provide useful information for estimating possible future drilling. However, present drilling appears to be well documented only for the petroleum industry. ADL estimates oil and gas drillings in 1976 and 1977 in the United States average approximately 0.04 holes drilled per year per possible repository site. Since the development of the petroleum industry is fairly recent, long term predictions based on present drilling rates may not be very accurate. Significant change could occur in the future for the following reasons:

1. Scarcity of oil, gas, water, or certain minerals may encourage more extensive exploration or make their use obsolete, so that exploration for them ceases.
2. New recovery methods or drilling techniques may make deposits or formations attractive which were previously not worth exploiting.
3. New resource recognition may initiate entirely distinct drilling programs.

Thus, any structured mathematical estimate of drilling frequency into a potential repository site is not very meaningful. The ADL report uses the following simple rationale for estimating the frequency of drilling into a bedded salt repository:

1. Persons in the future may drill to explore potentially economical deposits of petroleum and minerals.
2. In the course of their exploration, they will discover that the site has no valuable resources. Subsequently, however, this fact and the site location will be forgotton--or economic or social conditions will change--and exploratory drilling will occur again. ADL assumes the period of time to "forget" is 50 years, thereby assuming a frequency of 2 exploratory drillings per century.

Based on these premises, the estimated drilling frequency for the other generic repository types is compared with the frequency for bedded salt and is presented in Table 7-3.

We estimate the probability of impacting a canister during drilling by comparing the total area of the intersection of the drill hole and canister to the respository area. Assuming 35,000 canisters with an area of intersection of $0.2 m^2$ (ADL 79d) and a repository area of $8 km^2$, the probability of hitting a canister per drilling event is equal to product of the number of canisters and canister area divided by the area of the repository--or about 0.001.

The drilling frequencies assumed for shale are based on the same criteria as those for bedded salt. The drilling frequencies for basalt are based on the same types of exploration as bedded salt; however, ADL expects at least a factor of 2 decrease in the frequency of exploratory drilling in basalt compared to bedded salt based on a comparison of present drilling activity for basalt and bedded salt formations. Present drilling practices at domed salt formations indicate that the majority of the drilling is around the edges of the dome where petroleum or minerals are more likely to be found. ADL conservatively assumes the drilling frequencies will be the same at domed salt and bedded salt repositories. Presently, there is little reason to drill into or through a granite repository, although drilling to explore for geothermal resources is a possibility. The drilling frequency for granite is conservatively selected to be about a factor of 10 lower than the frequencies at any of the other reference repositories.

Drilling into a repository may lead to the release of radionuclides by several mechanisms, the principal ones being:

1. Direct impact on waste and transport of a fraction of it to the land surface.
2. Transport of radionuclide contaminated water from the repository to the surface.
3. Transport of nuclides with ground water to the upper aquifer through the backfilled but permeable borehole pathways.

The extent of releases depends on the degree to which the drillers recognize the repository and its associated hazards when they encounter it. If the drill bit passes directly into a waste drift backfilled with porous and unconsolidated material, an anomaly will probably be indicated by any of several signs, among them:

1. Rapid downward movement of the drill stem,
2. Loss of drill fluid,
3. Drill stem wandering and chatter,
4. Down-hole temperature changes caused by increased cooling of the drill by water in the repository. (This would only be detected in the case of constant thermal monitoring, as presently practiced in some geothermal exploration work).

The drillers might interpret these anomalies as an extensive shear zone or, if they have some idea that there is a repository in the area, they might identify it as such. If they did identify the unconsolidated zone as part of the repository, they would presumably exercise caution.

They could take samples of rock and water, employ down-hole logging and geophysical techniques, and grout or case the hole to seal off the repository during subsequent use of the drill hole. Or they might simply seal the hole and abandon that site.

Even if they fail to recognize the presence of a waste repository, it is likely the hole would be cased through the backfilled level--at least during the active life of the well. If, however, the drill were to pass through a rock pillar rather than a mined opening, recognition of the repository would be much less likely.

Despite the foregoing discussion, we have not assumed recognition of the repository by future drillers in our assessment. Our approach is based on three considerations:

1. The mined portion of the repository occupies only 25 percent of the total cross-sectional area.
2. The earlier assumption about loss of control and knowledge of the repository site makes it possible that anomalies encountered when drilling into a repository would simply be interpreted as a zone of incompetent rock.
3. Ignoring considerations about recognition of the site as a waste repository leads to a simple and conservative model.

If a drill bit hits the waste, some fraction of the contents of a canister will be transported to the surface. Based on an ADL analysis, the expected fraction of the canister intersected by a drill is approximately 0.15. ADL assumed the drill would pass right through the portion of the canister it intersects, which implies that this fraction also corresponds to the expected volumetric fraction of the contents that is raised to the surface. The quantity of radionuclides transported to the surface can be calculated using equation 5-1, with f= 0.15/35000 and t_e equal to the time the drilling event occurred:

$$Q = f\ Q_o e^{-\lambda t_e} \qquad (5\text{-}1)$$

Following impact of waste by a drill, the borehole may be sealed. The characteristics of borehole seals have been discussed previously. If the borehole interconnects the upper and lower aquifer, a pathway for groundwater flow is created. The release of radionuclides through this plugged borehole is described by equations 5-2a and 5-2b. The $V^*(t)$ term for volumetric flow in equation 5-2b can be described by Darcy's law for porous media and is discussed later for equation 5-28.

For drilling events that penetrate the repository but do not directly impact waste, the analysis is separated into two cases: repositories in salt and repositories in granite, shale, or basalt.

5.2.2.1 Salt Repositories

As discussed previously for expected releases, water can seep gradually into the backfilled repository through the somewhat permeable shaft and borehole seals. Since we assume a minimum volume of 20,000 m^3

remains in the repository, as much as 20,000 m^3 of water can leak into the backfill and remain there. In addition, fluid inclusions in the seemingly intact rock may migrate toward the waste canisters because of thermal gradients, thereby increasing the water content of the backfill close to the canisters. Water in the inclusions of the backfill may contribute to the dilution of radionuclides leaching into the void volume. Because a recent analysis indicates very little dilution can be attributed to fluid inclusions (NRC 80), we have ignored the included water.

Integrating the volumetric flow of water into the repository (equation 5-10 for bedded salt) over the repository closure time (200 years) yields 878 m^3 of water in the backfill. Using equation 5-11 for dome salt, the estimate is 736 m^3 of water. These estimates are slightly different than those calculated by ADL because ADL did not assume a minimum repository volume, V_{min}. The estimate for the volume of fluid released by a drilling event is based on the low porosity and low fluid availability at salt sites--and corresponds to the fluid surrounding two cansiters. Since we assume 35,000 canisters in the reference repositories, the volume of fluid released during drilling at a salt repository is estimated to be approximately $0.05m^3$ for bedded salt and $0.04m^3$ for domed salt.

Prior to a drilling event, the concentration of radioactivity in a brine pocket can be calculated using equation 5-4:

$$C(t) = f\ Q_0 e^{-\lambda t}[1-e^{-L(t-t_c)}]/V \tag{5-4}$$

In equation 5-4, f is the fraction of canisters contributing to the buildup of radioactivity in the brine pocket and V is the volume of water released during drilling. When a brine pocket is intercepted during drilling, we have assumed that the pressure in the pocket is high enough to eject the entire liquid contents into the drilling fluid, which is then carried directly to the land surface. The concentration calculated is multiplied by V to obtain the total quantity of radionuclides released to the land surface. If the radionuclide is solubility limited, the solubility limit, C_0, is multiplied by the volume V to calculate the total quantity released.

Following the release of a brine pocket to the land surface, the drilled borehole may or may not be sealed. In either case the hydraulic conductivity of the borehole shaft seal will not be zero. Recharge of the pocket is possible if the original drilling also intercepted the lower aquifer. If water is available, the empty pocket can be recharged and the remaining waste can leach radioactivity back into the pocket. Subsequently contaminated water can be transported up the borehole shaft to the overlying aquifer.

The equation describing the buildup and release of radioactivity to the aquifer from the brine pocket is calculated using equation 5-5:

$$V \frac{dC(t)}{dt} = LfQ_c(t) - \lambda VC(t) - V^*(t)C(t) \qquad \text{for } t > t_c \qquad (5\text{-}5)$$

where:

$Q_c(t) = Q_0 e^{-\lambda t} e^{-L(t-t_c)} \qquad t > t_c$

$V^*(t) = K(t)\ i(t)\ A\ c(\mu)$

A = area of borehole = 0.1 m^2

$K(t)$ = K+ K'(t-te), linearly increasing hydraulic conductivity for a borehole plug constructed at the event time t_e (m/yr). [Note: if the hole is not plugged or is plugged inadequately, K will not be small and K' will be 0. ADL conservatively assumed that the borehole will be filled in the same manner as an undetected borehole might be filled (ADL 79d). The hydraulic conductivity is then modeled to be uniform over time and to have an estimated value of 31.5 m/yr.]

$i(t)$ = hydraulic gradient from interconnection of the upper and lower aquifer and the gradient resulting from thermal bouyancy effects.

$c(\mu)$ = viscosity correction factor

These substitutions give the equation:

$$V \frac{dC(t)}{dt} = Lf\ Q_0 e^{-\lambda t} e^{-L(t-tc)} - \lambda VC(t) - K(t)i(t)c(\mu)AC(t) \qquad (5\text{-}28)$$

If the analytical expression for the product of the hydraulic gradient and the viscosity correction factor:

$$i(t)\ c(\mu) = ae^{-\alpha t} + be^{-\beta t} + ci_a e^{-\gamma t} + i_a$$

is substituted into equation 5-28, the solution to that equation can be written in the form of equation 5-6:

$$C(t) = \frac{1}{\mu(t)} \int_{t_e}^{t} \mu(s)q(s)ds + \frac{C(t_e)\mu(t_e)}{\mu(t)} \qquad (5\text{-}6)$$

where the parameters are defined as follows:

$$q(t) = L\ f\ Q_0\ e^{-\lambda t}\ e^{-L(t-tc)}$$

$$p(t) = \lambda + V(t)/V$$

$$\mu(t) = e^{\int^{t} p(s)ds} = e^{\lambda t}\ e^{\int^{t} V^{*}(s)/V\ ds}$$

$$V^{*}(t) = A\ [K + K'(t-te)]\ (ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a) \qquad (5\text{-}29)$$

and--because any radionuclides in solution when the drill penetrates the brine pocket are carried directly to the surface with the drilling fluid--the pocket is initially empty with regard to releases to the aquifer:

$$C(t_e) = 0$$

The solution to equation 5-28 for the specific example of $K' = 0$ is presented in Appendix C (C.6). The total quantity of radionuclide released to the aquifer is the integral of the product of $V^*(t)$ (equation 5-29) and the concentration $C(t)$ (the solution to equation 5-28). If the radionuclide is solubility limited, C_0, the limiting concentration is used in place of $C(t)$. If the volumetric flow is limited by the flow of the aquifer, then V_{aq} is used in place of $V^*(t)$ [see Appendix C (C.6)]. The parameters used to evaluate these equations for predictions of the amount of radionuclide released by drilling in salt repositories are summarized on Table 7-3.

5.2.2.2 Granite, Shale, Basalt Repositories

These rock types are considered to be hard rocks, and they do not exhibit the plastic flow or sealing phenomena of the salt media. Some types of shale may be plastic, but the type of shale considered in these analyses has characteristics similar to hard rock. Prior to any excavation, these hard rock formations are saturated with water. Excavation disturbs the saturation because water flows from the surrounding rock into the resultant cavity. During the operational phase of a repository, this water will be pumped out. After backfilling and closing the repository, water flowing down the filled shafts and/or through the rock walls will gradually fill the pores of the backfill until resaturation is completed. ADL estimates the longest time until the hard rock repositories reach resaturation is less than 200 years (ADL 79d). Some of ADL's other estimates indicate resaturation may take less than 10 years after sealing the repository.

The pore volume of the repository backfill can be calculated from the following equation:

$$V = A_r \, h \, M \, \eta \qquad (5\text{-}30a)$$

where:

A_r = area of the repository = 2 km×4km = 8km^2
h = height of the repository = 5m
M = mined fraction = 0.25
η = porosity of the backfill = 0.2

The repository backfill pore volume V equals 2×10^6 m^3. Once the canisters fail, radioactivity can leach into this saturated volume. Since the hard rocks do not flow plastically, the lithostatic pressure of the overburden will not close any of the repository pores. The pores are assumed, therefore, to remain interconnected and to act as a large mixing volume. Prior to any drilling event, the concentration of a radionuclide can be described by equation 5-4, with V equal to the pore volume in equation 5-30a and f equal to one:

$$C(t) = Q_o e^{-\lambda t} [1-e^{-L(t-t_c)}]/A_r nMn \tag{5-30b}$$

Drilling into a hard rock repository might transfer some contaminated backfill into the drill hole and up to the land surface. The backfill material is anticipated to be cohesive so that it will not easily wash into the drill hole (ADL 79d). Contaminated water might more easily wash into the drill hole and be transferred to the land surface. The quantity of water, V_b, predicted to be transferred to the land surface is 200 m^3—the volume of water contained in a 20 meter-long section of the waste drift centered at the drill hole (ADL 79d). The quantity of radionuclide transported to the land surface can be estimated by multiplying the concentration, C(t), from equation 5-30b and V_b, the volume of water transported to the land surface, yielding:

$$Q = \frac{V_b}{V} Q_o \, e^{-\lambda t} [1 - e^{-L(t-t_c)}] \tag{5-31}$$

If the radionuclide is solubility limited, then the quantity of radionuclide released is simply:

$$Q = V_b \, C_o \tag{5-32}$$

where C_o is the solubility limit.

Following a release to the land surface, the drilled borehole may or may not be sealed. In either case, the hydraulic conductivity of the borehole plug will not be zero. Contaminated water could flow through the pores in the plugged borehole to the overlying aquifer. Since the borehole pathway can release only a small fraction of the total volume of water, we have assumed that the concentration of radionuclides in the borehole pores will equal the total concentration described by equation 5-30b. This assumption is conservative and will result in a slightly larger calculated release than would actually occur. The quantity of radionuclide released to the aquifer to the time t_i uses the form of equation 5-8--with f=1, the concentration C(t) described by equation 5-30b, and the volumetric flow V*(t) described by equation 5-29--to yield:

$$Q = \int_{t_e}^{t_i} \frac{AQ_o e^{-\lambda t}}{V} [1-e^{-L(t-t_c)}][K + K'(t-t_e)](ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a)dt \tag{5-33}$$

For the granite repository, which does not have an underlying aquifer, and for drill holes that do not reach the underlying aquifer for shale and basalt, $i_a=0$ in equation 5-33. If the hydraulic conductivity is not changing (see discussion for equation 5-28), then $K' = 0$ and equation 5-33 simplifies to:

$$Q = \int_{t_e}^{t_i} \frac{AQ_0Ke^{-\lambda t}}{V} [1-e^{-L(t-t_c)}](ae^{-\alpha t}+be^{-\beta t}+i_a ce^{-\gamma t}+i_a)\, dt \qquad (5\text{-}34)$$

And if the concentration of the radionuclide is solubility limited, the solubility limit, C_0, replaces the concentration function $C(t)$ such that equation 5-34 becomes:

$$Q = AC_0K \int_{t_e}^{t_i} (ac^{-\alpha t}+be^{-\beta t}+i_a ce^{-\gamma t}+i_a)\, dt \qquad (5\text{-}35)$$

The parameters used to evaluate these equations for water released by drilling into repositories in granite, basalt and shale are summarized on Table 7-3.

5.2.3 Faulting

The discussion of faulting in this section is based primarily on the results of the ADL report, which indicate that--while detailed onsite data should be used for specific sites--repositories should generally be in geologically stable regions where renewed or new faulting is unlikely. Nevertheless, old faults are common in almost any location and may be expected at or near any repository site. We assume the presence of a certain number of faults on the site, and on the basis of their age and density, we estimate:

1. The probability of renewed movement along the old faults.
2. The probability of the occurrence of new faults.

The model assumes a constant probability based on the age of the most recent fault activity. Releases from the repository as a result of fault movement are assumed to be by groundwater flow to the overlying aquifer. The most important elements of this analysis are the reference fault characteristics, the estimation of probabilities, and the release model.

5.2.3.1 Reference Fault

The reference repository is 2 km wide and 4 km long. We conservatively assume that a fault intersects the repository parallel to its length. The width of the fault zone is assumed to be one meter, thus providing a 1 meter by 4000 meter pathway from the repository to the overlying aquifer. The widths of faults vary considerably, but fault zones wider than one meter are generally associated with growth during extended periods of activity. The porosity of the fault zone is assumed to be 0.1. The hydraulic conductivity of the fault depends on the strength of the host rock and is discussed separately for each repository.

5.2.3.2 Hydraulic conductivity

The hydraulic conductivity of the fractured zone associated with a fault in a salt repository can vary widely. Actually, instead of fracturing, the salt may simply deform to relieve the stresses that would induce fracturing in adjoining strata. Since salt is rather weak, any fracturing would be expected to produce fairly well crushed salt.

The hydraulic conductivity of compacted crushed salt has been estimated at about 31.5 m/year (ADL 79d). The shale overlying the bedded salt repository may have a lower hydraulic conductivity, but for conservatism the entire pathway from the lower aquifer to the upper aquifer is assumed to have the same hydraulic conductivity as the pathway through the salt.

The hydraulic conductivity of a fault through domed salt is assumed to be the same as for bedded salt. The hydraulic conductivity of shale is chosen to be 31.5m/yr and is based on the hydraulic conductivity for compacted crushed shale (ADL 79d).

Due to the high strength of granite, the hydraulic conductivity of the fractured zone of a granite repository site is based on the assumption that the granite is brecciated and fractured rather than pulverized. We believe a hydraulic conductivity of 3150 m/yr is a reasonable estimate (ADL 79d), although a large range of values is possible. This value of hydraulic conductivity corresponds to the high range for silty sand and gravel.

The hydraulic conductivity of basalt after faulting is assumed to be 3150 m/yr based on similar assumptions to those used for faulting at a granite site.

5.2.3.3 Probabilities

To estimate probabilities of renewed movement of old faults we need information on the time, N, since their most recent movement. We use the reciprocal of this time period, 1/N, to estimate the probability of renewed movement. If f faults are detected, then f/N, where N is the time to the most recent movement of any such fault, is used as a conservative estimate of the total probability of renewed movement. This assumption is made because movement along a fault can be regarded as a stochastic process, and intervals between movements are analogous to the time between failures of mechanical components in classical reliability theory. For example, suppose we know that, over the history of the fault, several time periods have elapsed between movements. The period N since the last movement should also be added to this list. Since fault movement has not yet recurred, N underestimates the true value of the time from the previous movement to the next movement, thus providing a conservative approximation of the probability of movement (see ADL 79d for further discussion). Often geologists assign a zero probability for renewed movement in the near future to certain old faults that are well dated and understood. It is expected that old faults at the repository site would fall into this category. We believe the estimation of a small positive probability is consistent with present practice and somewhat conservative (ADL 79d).

In attempting to estimate the probability of new faulting at a repository site, it is reasonable to consider only the most recent episode of faulting because, in general, earlier processes do not describe the present state of a site as well as recent processes. If this most recent episode of faulting and fault movement occurred during a period from M to N years before the present time period, and if the fault density of f faults per repository area was observed, then the average rate of new faulting over the last M years is given by f/M faults per year per repository. In a location with a long history of stability since the last faulting episode--and where no new geologic processes offer countervailing evidence--this average rate can be interpreted as a conservative estimate of the new faulting probability. In fact M is often more difficult to determine than N, and since N is less than M, the conservative larger probability, f/N, has been adopted for modeling purposes.

The combined rate of occurrence of either type fault movement is then given by 2f/N. With respect to the estimation of the parameter f, insufficient data is available for a generic statistical analysis. Some evidence for specific repository sites can be obtained by:

1. Examination of fault densities from surfaces maps.
2. Fault maps for power plant applications.
3. Seismic surveys for parts of the Delaware basin.
4. Reported fault spacing along anticlines in the Columbia Plateau.

On the basis of such data, it appears that--for most locations--it is very unlikely to find faults of the type discussed here spaced closer than about one to two kilometers, with 10 to 15 kilometers being more common (ADL 79d). Hence, we adopted an estimate of 2 faults per repository for all the reference repository models. Therefore, the selection of faulting probabilities for the various repositories only requires N, the last known occurrence of faulting.

5.2.3.3.1 Bedded Salt

The estimate for N for bedded salt is 230 million years, corresponding to the most recent faulting during the Permian age. This is generally a valid assumption for much of the Delaware Basin, for example (ADL 79d). Thus, the probability is calculated to be 2×10^{-8} events per year.

5.2.3.3.2 Domed Salt

The estimates for the faulting probabilities of domed salt repositories are based on data from the Gulf Interior region (ADL 79d). The youngest faults identified for the first estimates were dated at 13 million years when the domes stabilized, yielding a probability of 3×10^{-7} events/year.

5.2.3.3.3 Shale

The estimate for shale is based on the same geologic assumptions as those for bedded salt, giving the same probability of 2×10^{-8} events/year.

5.2.3.3.4 Granite

The ADL estimate for granite is based on the assumption of an ancient, stable batholith or other pluton. Some faulting would generally be expected following final emplacement or metamorphism. In western Massachusetts, ADL identified Triassic faulting as the most recent faulting associated with the Montague Power Plant (ADL 79d). This age ended 180 million years ago, resulting in an estimated probability of 2×10^{-8} events/year.

5.2.3.3.5 Basalt

The ADL estimate of the probability of faulting at a basalt repository site is based upon relatively stable areas of the Columbia Plateau, where the uppermost basalt layers, dated at 8 million years, show large areas free of faults. It is possible that the most recent faulting is still older than this, but there are active tectonic forces in the general region. An age of 8 million years yields a probability of $5\text{x}10^{-7}$ events per year.

5.2.3.4 Release Model for Faulting

The release model and associated assumptions for faulting should result in a conservative estimate of the flow rates to the overlying aquifer at a repository. The conservatism may overestimate flows by one or more orders of magnitude (ADL 79d). If the surrounding aquifers cannot support the flow rates calculated, then we assume that the volumetric flow rate is equal to that of the aquifers. Faults may heal either by plastic deformation of the surrounding rock or by the accumulation of fill material in the fractures. To simplify our calculations, these factors are not included in our model. To further simplify the repository model, we assume resaturation takes place before the fault movement occurs. In addition to the transport of radionuclides by groundwater flow through the faulted rock, there is the possibility that continued movement of the fault may lead to physical transport of a portion of the repository contents to the surface. ADL estimates show this process would be extremely slow (ADL 79d), and we did not include it in our assessment.

Derivation of the equations for estimating the release of radionuclides to the aquifer requires consideration of several processes. First, because of the possible leaching of radionuclides prior to a fault event, we assume the water saturating the backfill of the repository will contain a homogeneous concentration of each radionuclide throughout the backfill. As discussed previously, some radionuclides may be solubility limited rather than controlled by the waste form release rates. When the fault pathway is established, some of the contaminated fluid will mix with the fluid moving up from below so that some of the radionuclides in solution will be released. This effect decreases with distance from the fault. ADL assumes the zone of influence is a band extending 50 meters from each side of the fault. Such a zone is expected to contain 5 percent of the repository area and radionuclide inventory (ADL 79d). For the salt repositories, we agree with this assumption since there is limited interconnection of the brine pockets in bedded salt and domed salt repositories. However, in granite, shale, and basalt repositories we assume good interconnection of groundwater in the backfilll and the entire inventory of radionuclides--hence, we assume the entire repository is affected by the fault.

The mathematical equations describing the radioactivity in the water saturating the backfill are basically the same for all the repositories. They are also the same as those in section 5.1--only the assumptions of the parameters are different. The basic equation describing the concentration of the release is equation 5-5. The buildup of radioactivity in the pore volume prior to fault movement can be described by equation 5-3a. Thus, the form of the solution is the same as equation 5-6, with C(t) described by equation 5-4. We should note that f equals 1 and V equals 2×10^6 m^3 for granite, shale, and basalt. For the salt repositories, f = 0.05 and V = 1×10^5 m^3 (5 percent of the saturated volume of the hard rock repositories, as discussed above). Generally, the inventory of radioactivity in the pore volumes builds up until faulting occurs. For this case, the flow rate from the repository to the aquifer is described by equation 5-20 with the volumes, areas, and hydraulic conductivities presented in this faulting section. The gradient and viscosity terms are the same as those presented in equation 5-20. Parameters used in this section are summarized in Table 7-1.

In order to estimate the release of radioactivity from any waste in the actual path of the fault, we assume a fault damages 100 canisters--resulting in leaching of this waste directly into the aquifer. Equation 5-2a mathematically describes this phenomenon with f=100/35,000= 2.9×10^{-3}. For the solubility limited case, equation 5-2b applies.

Since the repository in granite does not have an underlying aquifer, the gradient is provided solely by thermal buoyancy and the recharge water is provided by the surrounding rock; this significantly restricts the groundwater flow rate. The repository in domed salt does not have an underlying aquifer either. It can be reasonably assumed, though, that a fault intersecting a salt dome will extend beyond the flank of the dome on one or both sides. Consequently, a connection will be established between the upper aquifer and an aquifer surrounding the dome below the level of the repository.

5.2.4 Breccia Pipes

Slow average rates of dissolution at the boundaries of the salt bed should not lead to breaches of the repository for tens or hundreds of millions of years. However, there are localized dissolution features that result from much higher than the average rates of salt removal. Deep dissolution processes at the bottom of bedded salt deposits can lead to the development of brine-filled cavities underneath the repository structure. These cavities, after reaching a certain critical size, can cause the collapse of the overlying rock and the propagation of a chimney of broken rock up to or toward the surface. Such a chimney structure is called a breccia pipe. This pipe provides a permeable pathway through which groundwater can flow and leach radionuclides from the waste. We assume fluid flows are upward, with the release of radionuclides into the upper aquifer. We assume that further dissolution of the salt formation around the breccia pipe at the repository horizon will not occur (based on qualitative considerations of water availability and degree of salt saturation), but we also assume there will be no healing of the column by cementation and recrystallization. Breccia pipes formed by localized dissolution are roughly circular, with diameters of a few tens of meters to more than 0.5 kilometers, and with an average depth three times the diameter. The upper portions are filled with broken rock called breccia, ranging from small granules to blocks a meter or more across. Relatively few measurements have been performed on the breccia filling the pipes to determine their hydrologic properties; however, existing data indicate that very broad ranges of porosity and hydraulic conductivity are possible. Pipes within the Carlsbad mining district in New Mexico have shown properties ranging from those of the intact evaporite section to those of typical gravels--with hydraulic conductivities from 3×10^{-5} m/yr to 3100 m/yr and porosities from one to twenty percent. At the time of formation, higher hydraulic conductivities are expected, in the range of 300 to 3×10^{5} m/yr.

The probability of occurrence of a breccia pipe on the repository site is specified in terms of a constant annual rate, except for an initial period of 500 years during which the probability is zero. An initial period of zero probability results from the fact that it takes some time for a critical cavity to develop, and if a pipe were already at a significant stage of growth at the time the repository were sealed, it would be detected by geophysical techniques (such as radar) operating from the mine. The time required for critical cavity growth is probably much longer than 500 years, but this conservative value has been adopted to account for the possibility that waste heat could induce more rapid dissolution. The probability of a breccia pipe developing at a repository is assumed to be 1×10^{-8} events/year.

To calculate this probability, ADL reviewed the literature and aerial photographs to estimate densities of possible breccia pipes in several evaporite basins. They calculated the volumetric rate of salt removal by deep dissolution and the time period during which this dissolution has been occurring. By comparing this rate with estimates of critical cavity size necessary for chimney initiation and propagation to an upper aquifer, ADL estimates the rate of breccia pipe formation. These estimates are comparable to estimates developed in other more empirical surveys--based simply on the number of features, basin area, and time period of dissolution processes. The resulting probability of occurrence is 1×10^{-6} yr^{-1}. ADL did not adopt this rate as the reference estimate, because they assume the avoidance of features that could lead to deep dissolution will have high priority in the repository site selection process. Their reference estimate is based on the assumption that the structures underlying a potential repository formation are simple and well mapped, and that any underlying aquifers are heavily saturated with salt, slow moving, at relatively low potentiometric head, and well isolated from the host salt formation in the vicinity of the repository. We believe these conditions can be verified with sufficient certainty to reduce the annual probability by two orders of magnitude, which leads to their reference estimate.

ADL chose the following parameters as representative of conditions in a newly formed breccia pipe:

$K = 10^{-2}$ cm/sec	(hydraulic conductivity)
$n = 0.2$	(effective porosity)
$A = 3 \times 10^4 m^2$	(cross-sectional area)

If a breccia pipe were to develop underneath the repository, eventually part of the repository would either slump or fall into the chimney-like structure. Physical damage to the waste package would be expected in this process, since the rock itself is rather thoroughly broken. At this point, the canisters would be subject to leaching by groundwater circulating from and back to an aquifer below the repository. The present model does not treat releases to the lower aquifer separately. Rather, since chimney growth propagates rapidly, we conservativley assume that a connection is established between upper and lower aquifers, and that water flows upward, driven by gradients from interconnection of aquifers and thermal buoyancy.

The canisters in the breccia pipe include about 0.4 percent of the repository inventory, based on the cross-sectional area given earlier. These canisters are subject to direct leaching. Furthermore, any radionuclides that had previously leached out of the waste packages would also be washed out with the groundwater flowing through the brecciated zone. We assume an area twice the diameter of the pipe itself is affected by this process, so that the cumulative leached inventory is 1.6 percent of the canisters' contents.

The mathematical equations for estimating the release of radioactivity to the aquifer are identical to those used for the faulting model. The only difference is the values of the input parameters, given above and summarized in Table 7-1.

5.2.5 Volcanoes

We do not expect anyone will purposely locate a repository site where future volcanic activity is likely. Nevertheless, volcanic trends can cover large distances over a period of time, and, occasionally, completely new volcanic centers erupt, even within stable crustal plates. This section of the report is concerned with the intersection of a repository by a volcanic structure that vents to the surface. The release model consists of a constant annual probability of a volcano penetrating a repository and transporting material to the air and land surface. Rates are estimated by counting the number of vents in various areas, dividing by their age to obtain vent formation rates, and multiplying by the probability that such a vent would intersect a randomly cited repository in the region of interest.

During the last ten million years, the only volcanism in the coterminous 48 States has been in the West. Most of this activity has paralleled the Pacific Coast, but some has followed the graben of the Rio Grande and an arc from Albuquerque toward Las Vegas, or has extended westward from Yellowstone Park.

Of concern for a repository siting are the frequency and predictability of new volcanism, since there are no present plans to consider placing repositories within the range of influence of known volcanoes. New volcanism will usually develop close to existing volcanic features and in regions experiencing tensional stress.

Areas of future volcanic activity can be defined only approximately, and predicting the timing of this future activity is even more difficult. Future estimates of the expected frequency of eruptive activity at volcanoes or in volcanic regions are generally based on historical records and geologic investigation, both of which vary widely in detail and reliability from one volcanic region to another. All of the geologic media considered in this study can be found in areas where there is no recent volcanism.

There are many site-specific factors that can enter into an estimation of the likelihood of future volcanism at a repository location. These include the distance to the nearest recent activity, whether the site lies in the direction of a trend, regional stress patterns and the way a site has evolved over geologic time (heat flow measurements, etc.). The model used here does not incorporate geophysical parameters, but rather utilizes a simple counting technique for roughly estimating the order of magnitude of the likelihood of future volcanism.

As noted earlier, all the vents in the coterminous United States that have shown activity within the last 10 million years are in the west. These events actually formed over a period longer than 10 million years; however, in estimating the rate of formation, it is conservative to use this shorter time span. ADL estimates approximately 1300 vents over a western area of the United States with a land area of 3×10^6 km^2. A gross regional average rate of vent formation is thus 4×10^{-11} vents/km^2/year. For a repository of area 8 km^2, the corresponding rate of intersection would be eight times the above, or 3×10^{-10} intersections per year. This number is used in an example calculation to represent the model equation of frequency equal to 8 V/AT intersections per year where V is the number of vents formed in the area A over a period at least as long as T. ADL chose the 10-million-year cut off for data on vents to conform to the USGS volcanic hazards maps.

A simple first estimate of the frequency for all media except basalt can be derived from the assumption that, with careful site selection, it should be possible to locate a repository so that the probability of future volcanism is less than the national average. This is because there are enough suitable bedded salt, granite, shale, and salt dome sites so that it should not be difficult to locate a repository in an area of very little past volcanic activity. The national average probability, therefore, is a conservative estimate of the frequency. This value is obtained exactly as above, except that the entire area of the conterminous states is used, so that the frequency is $(8)(1300)/(7.83 \times 10^6)(1 \times 10^7)$

or $1x10^{-10}$ intersections per year. Basalt is not covered by this reasoning because the only basalt deposits seriously considered as repository sites are located in a single region--namely, the Pacific Northwest. By their mere presence, basalts indicate significant past volcanic activity. Most of the Columbia Plateau flood basalts apparently were deposited about 14 to 17 million years ago, but some volcanic activity continues in locations such as Mount Lassen farther to the west. Regional stress studies suggest that there may be locations in this region where the probability of future volcanism is low. ADL based their calculations on the States of Washington, Oregon, and Idaho, exclusive of the north-south volcanic trend represented by the Cascade and Klamath Mountains. The following parameters have been estimated for this region:

$$A = 4x10^5 \text{ km}^2$$
$$V = 300 \text{ vents}$$
$$T = 10^7 \text{ years}$$

The resulting value of the frequency from the model equation is $6x10^{-10}$ intersections per year.

It should be noted that, in calculating the volcanic vent formation rate, the choice of regions to be considered has a great effect on the resulting numerical value. For example, application of the above procedure to the eastern United States would yield essentially zero rates. Simple modifications, such as eliminating from consideration the vents along the Pacific coast volcanic mountain zone, would indeed lower the rate for the rest of the country. Since this modification only changes the results by about a factor of 2, we do not believe it is important to refine them by making further site selection assumptions. Another modification we considered was to evaluate only intraplate silicic eruptions. While the consequences of these eruptions are more severe than those we evaluated, the analysis involves lower probabilities than the ones we have calculated. Also, an analysis of potential silicic eruptions involves detection of developing magma chambers that could lead to silicic eruptions over the next 10,000 years.

The dominant release mode for the interruption of a repository by a volcanic vent is the transport of radioactive material directly to the surface. Since the size of the vent and the nature of the eruption can vary considerably, this analysis simply estimates parameters that would characterize an "average" new vent. The area of the vent is taken to be $3x10^4$ m^2, corresponding to the area of a circle with radius 100 m. This cross-sectional area also characterizes the portion of the repository that would be affected: 0.4 percent of the repository inventory.

If we were to model the "worst possible" case in terms of consequences, then the probabilities would need to be revised downward accordingly. Equation 5-1 can be used to predict the quantity of a radionuclide ejected to the land surface by a volcano where $f = 4x10^{-3}$. The parameters discussed in this section are summarized in Table 7-1.

5.2.6 Meteorites

The impact of a large meteorite could cause a breach of the repository, either releasing material directly into the air and onto the land surface or by fracturing the surrounding rock, thereby permitting greater groundwater access. Meteorites large enough to create such breaches are very uncommon. Furthermore, the potential hazards associated with repository releases would appear to be negligible compared with the possible effects on surface installations, the environment, and the surrounding population; therefore, the following discussion will be brief.

From observations of cratering history on the inner planets and their satellites, and by correlation with the ages of portions of their surfaces (e.g., by lunar rock samples), estimates have been made of meteorite fluxes since the formation of the solar system. The ADL report (ADL 79d) discussses this rate since the early period of the solar system, when interplanetary debris was rapidly removed by the gravitational attraction of the planets. The rate appears to have been roughly constant for the last two billion years. Using data from well studied stable regions of the earth, a cratering production rate, ϕ, has been determined to be given by the following equation (ADL 79d):

$$\log_{10} \phi = -11.85-2 \log_{10} D \qquad (5\text{-}36)$$

where D is the crater diameter in km and ϕ is the number of craters per km^2 per year at least as large as the diameter D. It should be noted that D = 1 is near the lower limit of applicability of the given formula, but for present purposes--where the emphasis is on orders of magnitude--the formula suffices.

The geometry of craters is relevant in determining their effect on a nuclear waste repository. There are simple bowl-like craters, as well as ones with complex structures, including ringed ridges and peaks in the interior and depressed sections along the boundaries. Craters up to about 4 km in diameter in crystalline rock and 2-3 km in sedimentary strata are usually simple, while larger ones have complex structures. For a repository about 500 m deep, as in the generic models, a crater diameter of at least 1 km is a reasonable cutoff for defining meteorite events of interest.

The failure model concentrates on meteorites giving rise to craters of diameter 1-2 km because the frequency of meteorite cratering decreases rapidly with increasing size, and the larger size impacts are even more likely to cause widespread environmental effects of greater importance than breaching a waste repository. The target area has been taken to be 24 km^2, corresponding to the repository area (2 km x 4 km) and a 1-kilometer wide buffer zone around it. Failure occurs when the center of the crater lies within this area. Using the production rate of $\phi = 1.4 \times 10^{-12}$ per km^2 per year for craters of diameters of at least 1 km, the annual failure rate is 3×10^{-11} events per year. This rate is assumed to be independent of the host rock formation, since variations in geophysical properties are not significant for the purposes of these rough calculations.

A meteorite impact crater formed on the repository site would be expected to be smaller than the repository, since crater sizes are biased toward the lower end of the range under consideration. A crater of 1-km diameter would have a cross-sectional area at the surface of 0.8 km^2.

The breccia zone caused by a metorite would not even reach 500 m in depth, and the fracture zone at that depth would be very small. For a crater with a diameter of 2 km, the breccia zone would intersect the repository. Based on simple geometry, the area of intersection of the repository and the breccia zone is calculated to be about 0.8 km^2, corresponding to a circle 1 km in diameter. For our purposes, this area of intersection, of about 0.8 km^2, has been taken as a conservative estimate of the portion of the repository directly affected by the meteorite event. It has further been assumed that there is sufficient fracturing or brecciation down to the repository depth for direct releases to the surface to occur.

Because of the higher probability of meteorites at the low end of the size scale being considered, the expected direct release to the air and land surface is probably very small. Although there does not appear to be an analytical or empirical model for predicting this event, we have assumed that 1 percent of the wastes in the affected zone (i.e., 0.1 percent of the repository inventory) would be released to the land surface. The remaining wastes are subject to enhanced leaching by groundwater, but this pathway has been excluded in this evaluation, since the consequences of the aquifer pathway are expected to be much less than those for the direct release to land. Equation 5-1 can be used to predict the release to the land surface with f = .001. A summary of the parameters used in equation 5-1 for meteorites is presented in Table 7-1.

Chapter 6 - ENVIRONMENTAL PATHWAYS

The calculation of population doses and health effects due to radioactive releases from a repository requires that each environmental pathway be identified. We used very general models of environmental pathways to convert the radionuclide releases to somatic and genetic health effects. Population distributions, food chains, and living habits will undoubtedly change in major ways over 10,000 years. Rather than attempt to predict these changes, we generally chose parameters similar to today's to use in these models. A detailed discussion of the techniques and assumptions discussed in this chapter is presented by Smith, et al. (SMJ 82).

There are four general release modes: radionuclide releases through an aquifer to a river (surface water), releases via a river to an ocean, releases directly to a land surface, and releases directly to air. For each of these release modes we calculated the dose equivalents for each organ and radionuclide for all the releases and environmental pathways concerned. The organs we evaluated are bone, red marrow, lung, liver, GI-LLI, thyroid, kidney, ovaries, testes, and total body. Total body dose equivalents were used as an approximation for doses to all soft tissues not otherwise specified. From the dose equivalent for each organ, we calculated the expected fatal cancer and genetic effects for each person exposed to the radioactivity. These fatal and genetic effects are called health effects or health impacts. We estimated only the genetic effects which are clinically significant enough to require medical treatment.

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Total health effects involve summing all the expected fatal or genetic effects over the exposed population.

6.1 Releases to a River

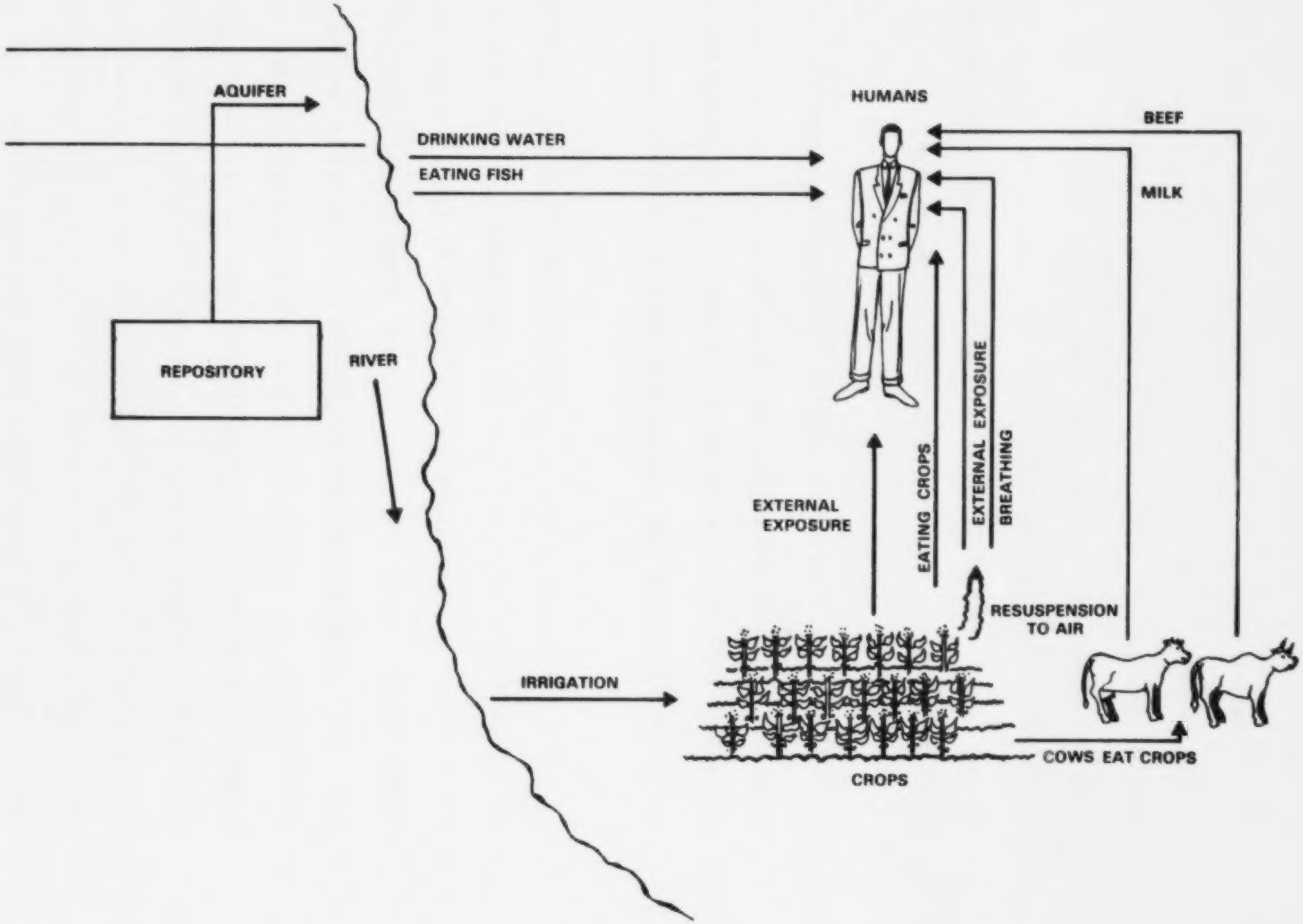
For the river release mode, we assume the repository is breached so that groundwater can circulate through the repository and transport radionuclides through an aquifer overlying the repository. These radionuclides are eventually released to a river. The total amount of a specific radionuclide entering the river is determined by integrating the release rate over the time period of interest.

When the radionuclides reach the river, we assume they are immediately diluted in the river flow. We calculated the concentration of nuclides in the river by dividing the release rate by the river flow rate. This concentration is used to compute the population environmental dose commitment and the resulting health effects for a population exposed through the following pathways:

-- drinking water
-- eating fish
-- eating food raised on irrigated land including vegetables, milk and meat
-- inhaling material resuspended during irrigation
-- being directly exposed to radiation from nuclides deposited on land surface
-- being directly exposed to radiation from nuclides resuspended in air

Figure 6-1 illustrates these pathways.

FIGURE 6-1 SCHEMATIC OF A RELEASE TO RIVERS


AQUIFER
REPOSITORY
RIVER
DRINKING WATER
EATING FISH
HUMANS
BEEF
MILK
EXTERNAL EXPOSURE
EATING CROPS
EXTERNAL EXPOSURE
BREATHING
RESUSPENSION TO AIR
IRRIGATION
CROPS
COWS EAT CROPS

We estimated the total intake of radionuclides by the population utilizing the river and its food products. People living along the river ingest radionuclides dissolved in the river water if the water is used for public consumption. The annual intake by the population is calculated from the amount of water an individual drinks (ICRP 75), the number of individuals drinking the water, and the radionuclide concentration in the water. We assume there is no reduction of radionuclide concentrations in drinking water due to water treatment, sedimentation, or river use.

Fish in the river also take up radioactivity dissolved in the river water. These fish are caught and consumed by the public. We used estimated fish ingestion rates by the public to determine the total intake by the population of the various nuclides in the river water.

The river water containing radionuclides from the repository is used to irrigate farm land used to raise vegetables and fruit and to graze milk and beef cattle. We assume all irrigation is spray irrigation, with direct deposition of the spray onto the crops and the land surface below the crops. Some of the radioactive material deposited on the ground moves down into the soil and is taken into plants through the root system. This augments the material deposited directly on the plant surfaces. We assume some of the irrigated plants are consumed by humans as food and the rest are consumed by milk or beef cattle. Consumption of contaminated vegetation by milk or meat producing animals results in transfer of radionuclides to milk and meat. Thus, the overall result of using contaminated river water for irrigation is that radionuclides in vegetables and fruits, milk, and meat are ingested by humans. Ingestion rates of the food products contaminated as a result of irrigation with river water are used to estimate the total radionuclide intake by the population.

Some of the radioactive material deposited onto soil by spray irrigation is resuspended into the air. We estimated the resulting integrated air concentration using a resuspension factor and then calculated the ingestion of radionuclides by the affected population using a representative inhalation rate for the population. The equation used to compute the population dose requires an estimate of population density within the assessment area.

The radioactive material deposited on the ground during irrigation also results in external doses to persons in the area. During the period of time that irrigation takes place, radioactive material continues to build up on the ground until either the irrigation stops or equilibrium is reached. The dose rate to the population receiving this external dose is computed using external dose rate factors, population density, and a shielding and occupancy factor to estimate the population dose for each organ due to ground contamination.

These radionuclide intakes and external exposures are combined with organ specific dose commitment factors to calculate population dose equivalent commitments for each organ. Health effect factors are then used to convert population dose commitments to organ specific fatal and genetic health effects. The health effects for all organs are added to obtain total fatalities and genetic defects.

6.2 Releases to the Oceans

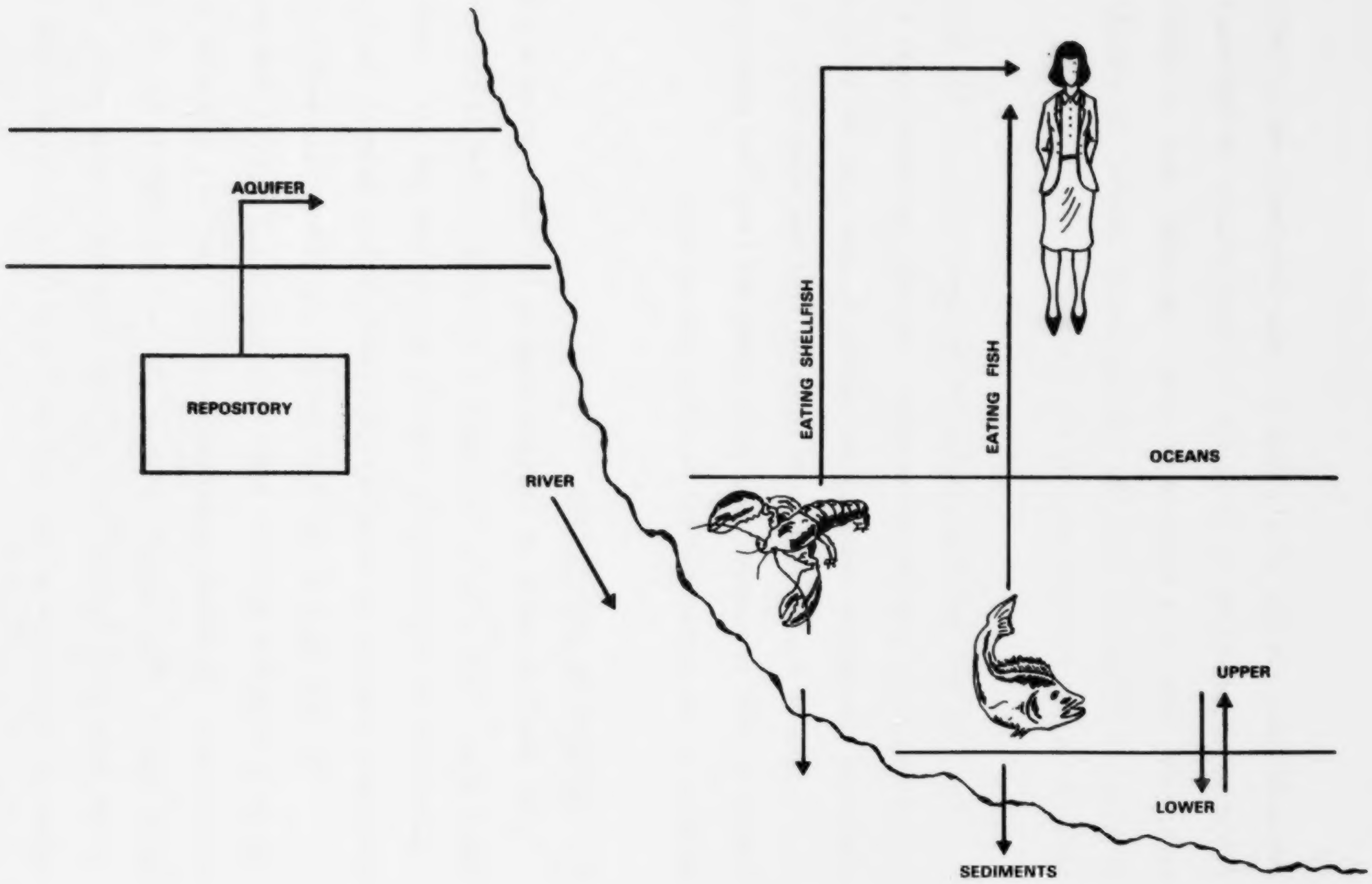
We assume radionuclides from a waste disposal facility are transported to the ocean through a river system. Other assumptions are:

- Travel time in the river to the ocean is negligible
- Depletion of radionuclides in the river due to removal by irrigation and sedimentation is not considered.

In light of these assumptions, the radioactive releases to the oceans are the same as those releases to the river.

To calculate the radionuclide concentrations, the oceans are divided into two vertical compartments: a 75-meter thick upper layer in which we assume all edible seafood is grown, and a deeper lower layer. Our model includes a slow transfer of radionuclides between these two layers. Figure 6-2 illustrates these two layers or compartments. To be conservative, we assume all edible seafood is in the upper layer--since we expect radionuclide concentrations in the upper layer to always be higher than those in the lower layer. Radionuclides are transferred between the two layers and removed from the ocean by radioactive decay and

FIGURE 6-2 SCHEMATIC OF THE OCEAN PATHWAY


AQUIFER
REPOSITORY
RIVER
EATING SHELLFISH
EATING FISH
OCEANS
UPPER
LOWER
SEDIMENTS

sedimentation. Smith, et al. (SMJ 82) have developed and solved coupled differential equations to calculate the concentration of radionuclides in each ocean layer as a function of time. The upper layer concentration equation is integrated over the time period of interest to compute the total intake of radioactivity by the public.

The fish and shellfish living in the upper layers of the ocean take up radionuclides from the ocean water. We used estimated ocean fish and shellfish consumption rates by the public to determine the total population intake of the radionuclides released from the repository. This intake is used to compute population doses and fatal and genetic health effects in the manner similar to river release mode.

6.3 Releases to Land Surface

We assume releases of radionuclides to the land surface are to a small area. This area is considered a point source for calculating resuspension of radioactivity from the ground into the air. Several processes interact to distribute the radionuclides between the air and soil. Radionuclides on the land surface are either resuspended into the air or transported into the lower soil layers and removed from the environment. We assume resuspended radionuclides are dispersed from a point source. The concentration of the radionuclides in the air depends on the time after release, the distance from the release point, and the amount of deposition on the land surface that has occurred since the release.

We used a dispersion equation and deposition rate to the land surface to calculate air concentrations. The result is an air concentration and a ground surface concentration of radionuclides as a function of distance from the release point and the time after the release.

The radiation dose pathways to the population which we consider important are:

- eating food raised on land contaminated with radionuclides, including vegetables, milk, and meat
- inhaling radionuclides
- being exposed to radiation from nuclides resuspended in air
- being exposed to radiation from contaminated land surface

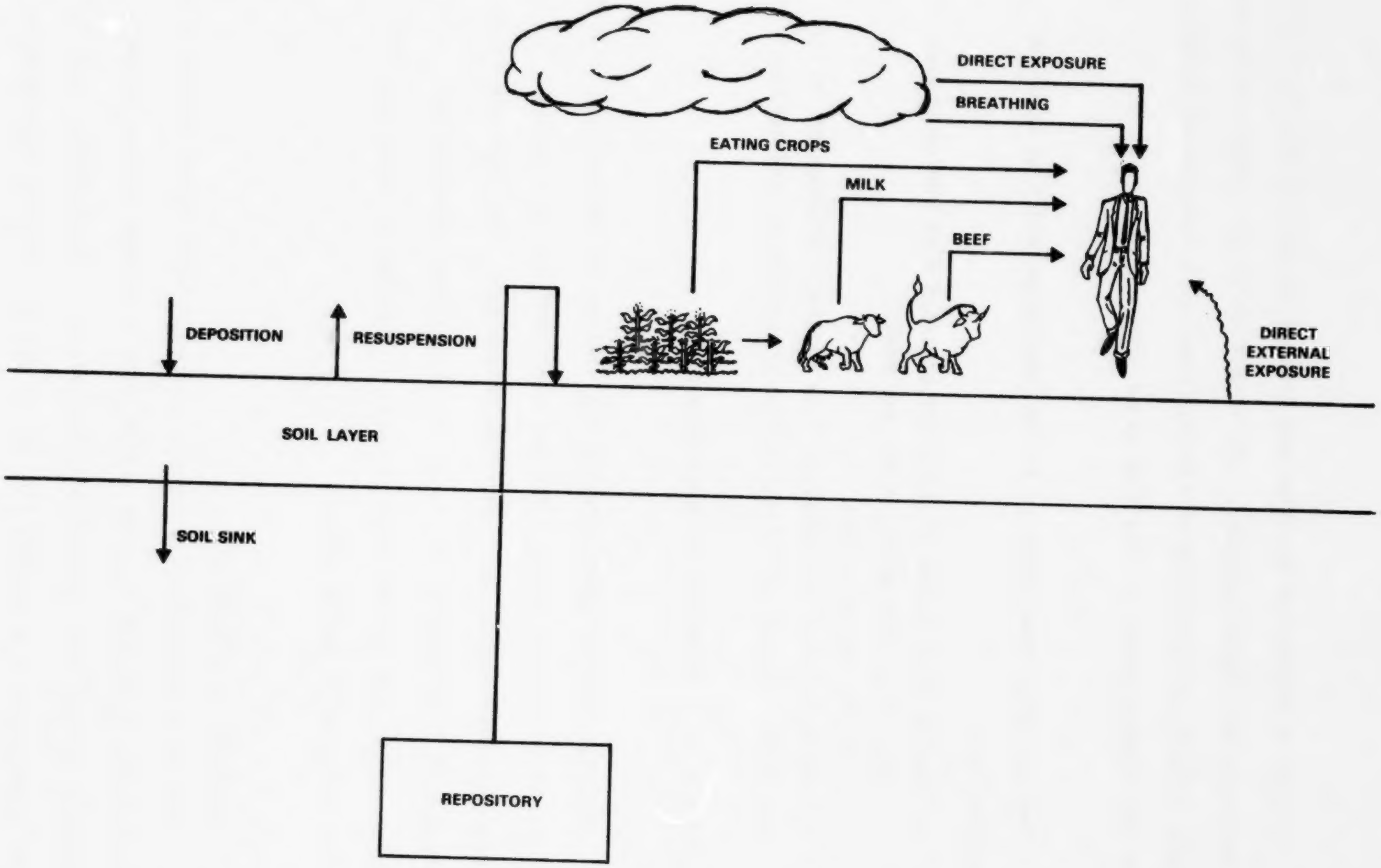
Figure 6-3 is a schematic of these pathways.

These population dose pathways are similar to the pathways discussed for the river release model. The basic assumptions are the same for each similar pathway and do not need to be reiterated. The approach is to compute the total population intake of or external exposure to radionuclides and convert these intakes to population doses and then to fatal and genetic health effects.

6.4 Releases to Atmosphere

Violent disruption of a repository can release wastes directly from the repository to the air. We assume such a violent release disperses the material so that the radioactivity is eventually distributed uniformly in the troposphere in a fashion similar to fallout from nuclear weapons.

FIGURE 6-3 SCHEMATIC OF THE LAND SURFACE RELEASE


DIRECT EXPOSURE
BREATHING
EATING CROPS
MILK
BEEF
DEPOSITION
RESUSPENSION
DIRECT EXTERNAL EXPOSURE
SOIL LAYER
SOIL SINK
REPOSITORY

We assume radionuclides that fallout over the land surface are distributed uniformly in a volume equal to land surface area of the earth multiplied by the average height of the troposphere. With the material distributed in this manner, we develop a two compartment mathematical model to predict radionuclide movement between the air and the land surface. The upper compartment is the tropospheric volume above the earth, and the lower compartment is the available land layer (i.e., the layer of land containing the soil surface as an upper boundary and including the root zone or plow layer of soil). This approach is very simplistic; however, we believe a more detailed model is not needed. One reason for not using a more detailed model is the low probability of the events, such as volcanoes and meteorites, that release radionuclides into the air.

Radionuclides are transported between the two compartments by resuspension from the soil surface to air and by deposition from air to the soil surface. The radionuclides are removed from man's environment by radioactive decay and transport from the soil surface to the lower, unavailable soil layers. To obtain the quantities of radionuclides in these two compartments, we have developed and solved a system of two coupled differential equations. Using these solutions, we obtain time-dependent air and ground surface concentrations of radionuclides, which are in turn used to compute population doses and health effects.

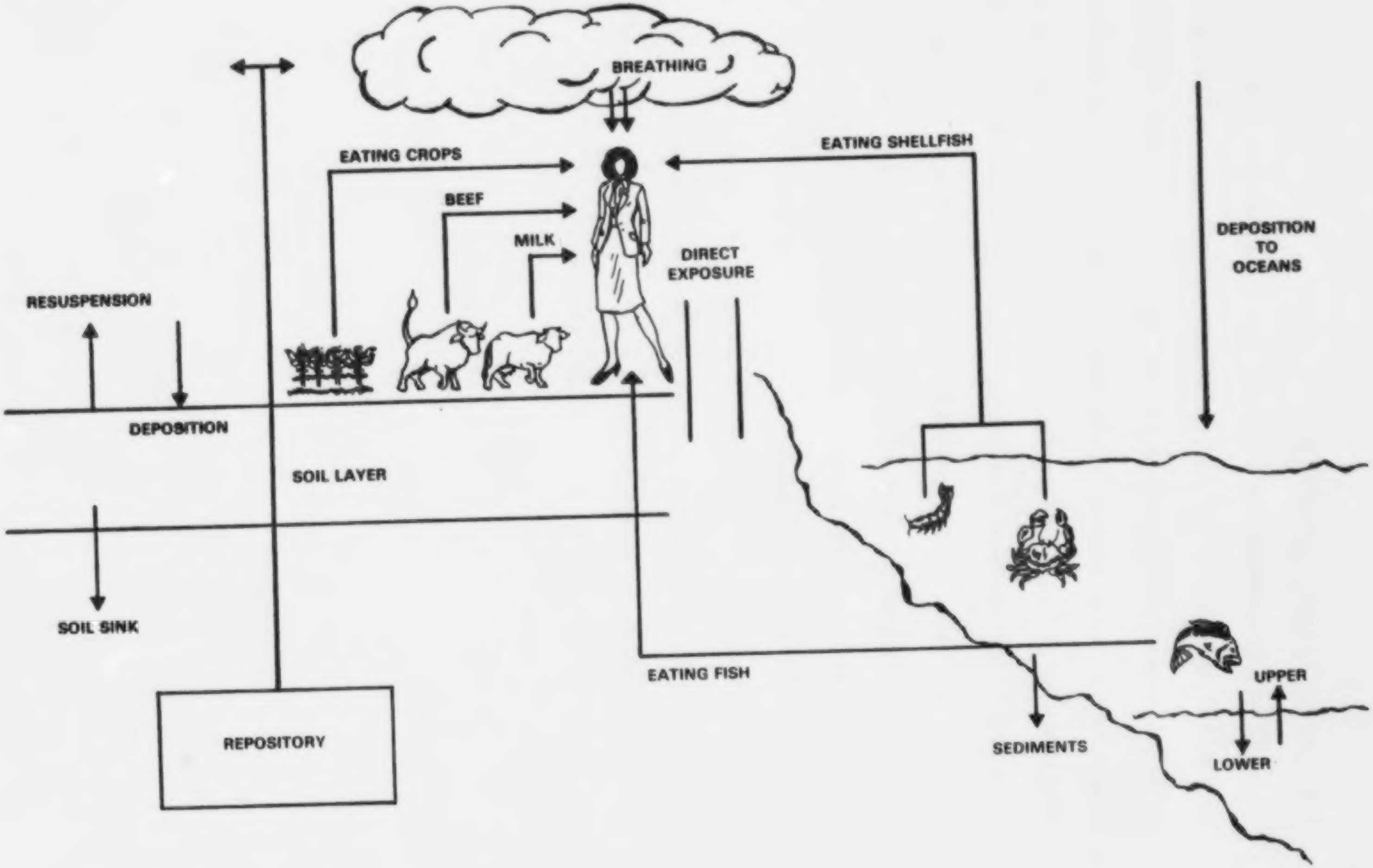
Since radionuclides are present both in air and on the ground as a result of the release to the air-over-land, the important radiation dose pathways to the population are:

- ingestion of food raised on land contaminated with radionuclides, including vegetables, milk, and meat
- inhalation of radionuclides
- external exposure due to air submersion
- external exposure due to ground surface deposition

Figure 6-4 is a schematic of these pathways. The assumptions used to calculate the doses and health effects for these pathways are similar to those discussed earlier for the other release modes.

We assume the radionuclides released to the air over the oceans are distributed uniformly in a volume determined by multiplying the earth's ocean area by the average height of the troposphere. With the material distributed in this manner, a three-compartment model is established to describe radionuclide movement between the troposhpere and the two ocean compartments. Using this model, concentrations of radionuclides can be determined as a function of time in the air and in each of the two ocean compartments, which were described earlier. The radionuclides in the air compartment are transferred into the ocean by deposition similar to fallout. A system of three differential equations, two of which are coupled, are written and solved to obtain the water concentration of radionuclides in the upper ocean layer. From the concentration of radionuclides in the oceans, we calculate total fatal and genetic effects.

FIGURE 6-4 SCHEMATIC OF THE RELEASE TO AIR


BREATHING
EATING CROPS
BEEF
MILK
EATING SHELLFISH
DIRECT EXPOSURE
DEPOSITION TO OCEANS
RESUSPENSION
DEPOSITION
SOIL LAYER
SOIL SINK
REPOSITORY
EATING FISH
SEDIMENTS
UPPER
LOWER

6.5 Health Effects Calculations

Using the methodology developed by Smith, et al. (SMJ 82), we determined the population health effects (fatal cancers and genetic effects) that could be caused by radioactivity released from the repository through each of these four release modes. In general, we developed an estimated value for the health effects caused for each curie of a particular radionuclide released through a particular release mode. For this analysis, we assumed that releases to rivers ultimately become releases to oceans (without reducing the ocean release for any depletion due to the processes encountered during transit in the river). Thus, we added the health effects caused by a curie released to a river and an ocean to develop a value for health effects per curie released to "surface water." Table 6-1 displays the parameters we used to calculate the health effects caused by releases to surface water, land surface, and the air. The data used to develop these values are described in Smith, et al. (SMJ 82).

Table 6-1

Health Effects per Curie Released for Different Release Modes

Nuclide	Releases to Surface Water	Releases to Land Surface	Releases to the Air
Am-241	7.31 E- 1	8.98 E- 2	1.59 E- 1
Am-243	2.77 E 0	1.03 E 0	1.14 E 0
C- 14	4.58 E- 2	2.58 E- 5	2.04 E- 4
Cs-135	3.83 E- 3	4.01 E- 4	7.36 E- 4
Cs-137	1.98 E- 2	5.62 E- 4	6.91 E- 3
I-129	1.09 E- 2	2.31 E- 5	1.38 E- 3
Np-237	5.98 E- 1	3.22 E- 3	8.03 E- 2
Pu-238	2.29 E- 2	3.21 E- 3	1.47 E- 2
Pu-239	6.93 E- 2	5.55 E- 2	5.18 E- 2
Pu-240	6.54 E- 2	4.94 E- 2	4.76 E- 2
Pu-242	6.77 E- 2	5.63 E- 2	5.13 E- 2
Ra-226	3.17 E 0	8.42 E- 2	4.87 E- 1
Sr- 90	1.21 E- 1	9.75 E- 4	1.63 E- 2
Tc- 99	2.86 E- 4	6.03 E- 8	3.67 E- 5
Sn-126	1.20 E- 1	4.13 E- 2	1.12 E- 1
U-234	1.34 E 0	5.70 E -1	6.13 E- 1
Zr- 93	6.94 E- 2	1.82 E- 1	1.55 E- 1

Chapter 7 - RESULTS

We present the results of our analysis in terms of the consequences (fatal cancers and genetic effects) and the probability of those health effects. Our approach is to generate a probability and consequence for each event and each event time selected, and to prepare a cumulative complementary distribution function (CCDF). We also multiply each probability (P) by its associated consequence (C) and sum the products to obtain an overall risk, which we call the "(P)(C) risk", "expected value", or the "expected health effects" over some period of time. To determine the importance of different model assumptions we vary the characteristics of the reference models.

To construct the CCDF graph, we first rank the consequences (highest consequence first) and then associate with each consequence the sum of its probability plus the probabilities of all the higher consequence events. The consequence (horizontal axis) of the highest consequence event is plotted against its probability (vertical axis). The next lower consequence event is then chosen and its consequence is plotted against the sum of its own probability plus the probability of the higher consequence events. Each point on the resulting graph then gives the probability of obtaining at least the indicated number of consequences or health effects.

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The CCDF graph gives not only the "expected value" (by integrating the area under the graph), but also indicates the distribution of consequences. The consequences calculated can be fatal health effects, genetic health effects, or weighted release ratios. The weighted release ratios are the summation of the releases in curies of each radionuclide divided by the quantity of each radionuclide corresponding to the release limits in EPA's proposed environmental standards for high-level waste disposal (EPA 82).

In developing the probabilities and consequences of the various events, we identified three categories: (1) releases from events which are not expected to occur within the time of interest (i.e., volcanoes, meteorites, faults, breccia pipes), (2) releases from events which are expected to occur a few times to hundreds of times during the time of interest (i.e., human intrusion), and (3) releases which we expect will occur continuously during the time of interest (i.e., normal groundwater flow).

7.1 Releases from Low Probability Events

The frequencies at which the low probability events occur are assumed to be constant annual rates. To calculate the necessary probability/consequence information, we chose several time intervals and calculated the cumulative probability of an event over each time interval using the following equation:

$$P_{cum} = P_{ann} (t_{i+1} - t_i) \tag{7-1}$$

where P_{cum} equals the total probability of an event with an annual probability (P_{ann}) occurring over the time interval $t_{i+1}-t_i$. The event is assumed to occur once in each time interval at the midpoint of the interval:

$$t_e = (t_i + t_{i+1})/2 \qquad (7\text{-}2)$$

The health effects are calculated for each event occurring at t_e, and then integrated from t_e to the final time of interest t_f.

The CCDF curves can be obtained by matching sets of cumulative probabilities (P_{cum}) and integrated health effects. The expected number of health effects for one event in a time interval is the product of the cumulative probability P_{cum} for the time interval and the integrated health effects for the event occurring in the time interval. The total expected health effects for the event over the entire time of interest (from t=0 to $t=t_f$) can be calculated from equation 7-3:

$$\text{total expected health effects} = \underset{i}{} P_{cum_i} He_i \qquad (7\text{-}3)$$

where:

$P_{cum_i} = P_{ann}(t_{i+1} - t_i)$

He_i = integrated health effects from t_e to t_f for each i interval

$t_e = (t_{i+1} + t_i)/2$

t_f = 10,000 years, for most of our calculations.

7.2 Releases from High Probability Events (Human intrusion)

We expect inadvertant human intrusion to occur more than once during the time of interest. The expected frequency of human intrusions into a repository ranges from a drilling event every 400 years for granite to a drilling event every 50 years for salt and shale (ADL 79d). An evaluation of the total health effects from drilling events may cover thousands of years--with tens to hundreds of drilling events expected during the time of interest. Drilling events which may impact waste, however, are expected to occur only once every one thousand drilling events. Even over many thousands of years, it is possible that no direct impact of a canister would occur. Thus, the direct hit of a canister is handled mathematically as a low-probability event. Drilling events that do not directly impact waste but do interact with contaminated groundwater in the repository are expected to occur many times.

To evaluate these higher probability events in conjunction with the low probability events, we must generate sets of probabilities and consequences. Human intrusion may occur any time after institutional controls have been removed--and can be assumed to be random in nature. We assume that a binomial distribution, the fundamental statistical law that governs random events, is applicable to human intrusion. The probability that exactly n events will occur over a time period between t=0 and $t=t_f$ can be expressed by:

$$P_n = \frac{t_f!}{(t_f-n)!n!} P_{ann}^{n} (1-P_{ann})^{t_f-n} \qquad (7\text{-}4)$$

For convenience, we assume that--if n events do occur--they are equally spaced over the time of interest. Thus, the average time between events can be calculated from equation 7-5:

$$t_{av} = (t_f - t_{in})/(n+1) \tag{7-5}$$

t_{in} = institutional control time period, years

The first event time is $t_{in}+t_{av}$, the second event time is $t_{in}+2t_{av}$, etc., until the final event time, which is t_f-t_{av}. The integrated health effects are calculated for each event time and summed to obtain the total health effects over the time of interest for n events. In this way we have generated sets of cumulative probabilities and health effects for the high probability of n events. From this data, the CCDF and the total expected health effects can be calculated and integrated with the data from the low probability events.

7.3 Releases from Normal Groundwater Flow

Releases from normal groundwater flow occur once with a probability of one over all time. Thus, the integrated health effects are calculated over the time of interest. This data can be used directly for the CCDF and the expected health effects with a probability equal to 1. The expected releases include bulk rock transport for granite, shale, and basalt repositories and the leakage (if any) through boreholes and shafts for the salt repositories.

7.4 Results for Reference Repositories

To evaluate the effects of different assumptions on the long-term risks from the five types of repositories, we first analyzed the risks associated with each of the reference repositories. The various parameters of our reference repositories and the characteristics of the release mechanisms have been presented throughout the report. For convenience the parameters for the release mechanisms are summarized in Tables 7-1 through 7-3.

We present the results for the reference repositories in two formats: (1) graphs of cumulative probability versus premature cancer deaths (CCDF curves) and (2) total expected premature cancer deaths (probability times consequences). Most of our calculations evaluate a 10,000 year period after repository closure. This time frame was chosen for two reasons: (1) it is long enough for releases through groundwater to reach the environment, thus allowing us to evaluate the importance of the geochemical properties of the surrounding aquifers, and (2) it is short enough for the probabilities and characteristics of geologic probabilities and characteristics of geologic events which might disrupt the disposal system to be reasonably predictable.

The CCDF curves for four of the five reference repositories are presented in Figures 7-1 and 7-2. The CCDF curve for the salt dome repository has not been included since it is essentially the same as the one for bedded salt. The expected somatic health effects (premature cancer deaths) for each event type and each repository are shown in

Table 7-1

Characteristics of Low Probability Events

(Faults, Breccia Pipes, Volcanoes, Meteorites)

Faulting

Fraction of repository breached		3 E- 3
Porosity of fault zone		1 E- 1
Fraction of repository affected:	Bedded Salt, Domed Salt	5 E- 2
	Granite, Shale, Basalt	1.0
Volume of repository affected (m^3):	Bedded Salt, Domed Salt	1 E+ 5
	Granite, Shale, Basalt	2 E+ 6
Hydraulic conductivity of flow path (m/yr):	Bedded Salt, Domed Salt, Shale	31.5
	Granite, Basalt	3 E+ 3
Cross-sectional area of fault (m^2)		4 E+ 3
Probability (yr^{-1}):	Bedded Salt, Granite, Shale	2 E- 8
	Domed Salt	3 E- 7
	Basalt	5 E- 7

Breccia Pipes (Bedded Salt Only)

Fraction repository breached	4 E- 3
Fraction of repository affected	1.6 E- 2
Probability after first 500 years (yr)	1 E- 8
Flow area (m^2)	3 E+ 4
Porosity of flow path	2 E- 1
Hydraulic conductivity of flow path (m/yr)	3 E+ 3

Volcanoes

Fraction of repository breached		4 E- 3
Probability (yr^{-1}):	Bedded Salt, Domed Salt, Granite, Shale	1 E-10
	Basalt	6 E-10

Meteorites

Fraction of repository breached	1 E- 3
Probability (yr^{-1})	4 E-11

Table 7-2

Characteristics of Normal Groundwater Flow

Bulk Rock Transport (Granite, Basalt, Shale):

	Granite	Basalt	Shale
K, hydraulic conductivity (after 100 years), m/yr	3×10^{-4}	3×10^{-3}	3×10^{-3}
A, cross-sectional area of flow path, m^2	8×10^{6}	8×10^{6}	8×10^{6}
$i(t)\ c(\mu) = ae^{-\alpha t} + be^{-\beta t}$	where:		
$a =$	.0132	.132	.132
$b =$	.0102	.102	.102
$\alpha =$	1.6×10^{-3}	1.6×10^{-3}	1.6×10^{-3}
$\beta =$	3.1×10^{-4}	3.1×10^{-4}	3.1×10^{-4}

Shaft and Borehole Leakage (Bedded Salt, Domed Salt):

Initial Hydraulic conductivity of Shafts and Boreholes, m/yr		3.2×10^{-3}
Annual change in Shaft seal, m/y^2		3×10^{-5}
Annual change in Borehole seal, my/yr^2		3×10^{-4}
Hydraulic gradient of upper aquifer:		
	Bedded Salt	1.3
	Domed Salt	1.1
Viscosity Coefficient		5.0
Area of Main Shafts, m^2		100
Area of Boreholes, m^2	Bedded Salt, 60 holes	6
	Domed Salt, 50 holes	5
Repository Closure Time, years		200
Minimum recharge volume, m^3		20,000
Lithostatic gradient		7.9

Table 7-3

Characteristics of High-Probability Events

(Human Intrusion by Drilling)

Characteristic	Bedded Salt	Domed Salt	Granite	Basalt	Shale
Drilling (hit canister)					
Fraction of repository (.15 of 1 canister)	4E-6	4E-6	4E-6	4E-6	4E-6
Probability (yr^{-1})	2E-5	2E-5	2.5E-6	1E-5	2E-5
Drilling (missed canisters)					
Fraction of repository	6E-5	6E-5	1.0	1.0	1.0
Volume of affected repository (m^3)	.06	.04	2E6	2E6	2E6
Volume of repository removed by drill (m^3)	.06	.04	200	200	200
Initial permeability (m/yr)	3E-3	3E-3	3E-3	3E-3	3E-3
Rate of change of hydraulic conductivity (m/yr^2)	3E-4	3E-4	3E-4	3E-4	3E-4
Porosity in flow path	.1	.1	.1	.1	.1
Area of flow path (m^2)	.5	.5	.5	.5	.5
Probability (yr^{-1})	2E-2	2E-2	2.5E-3	1E-2	2E-2

Figure 7-1: COMPLEMENTARY CUMULATIVE DISTRIBUTION FUNCTIONS
(Bedded Salt and Granite)

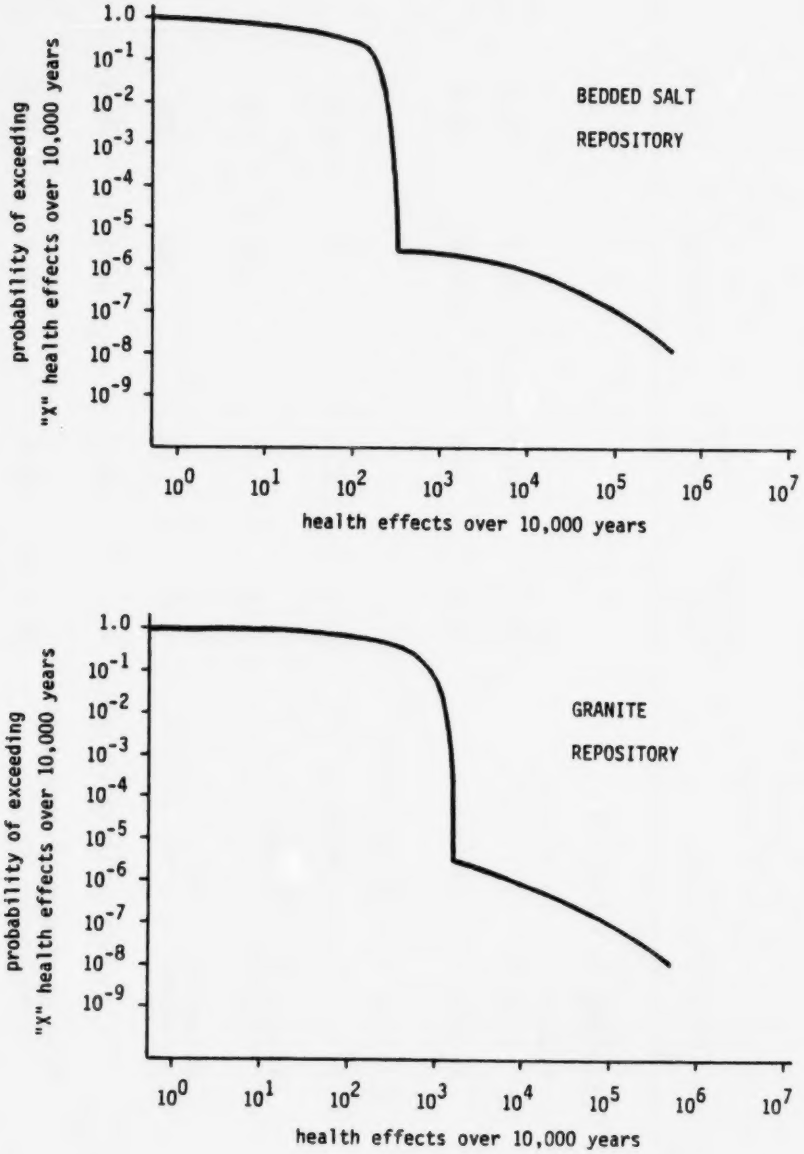
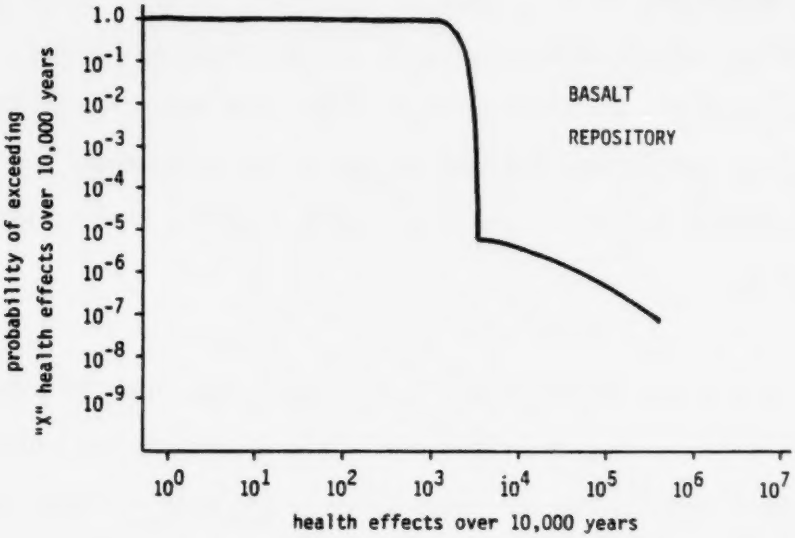
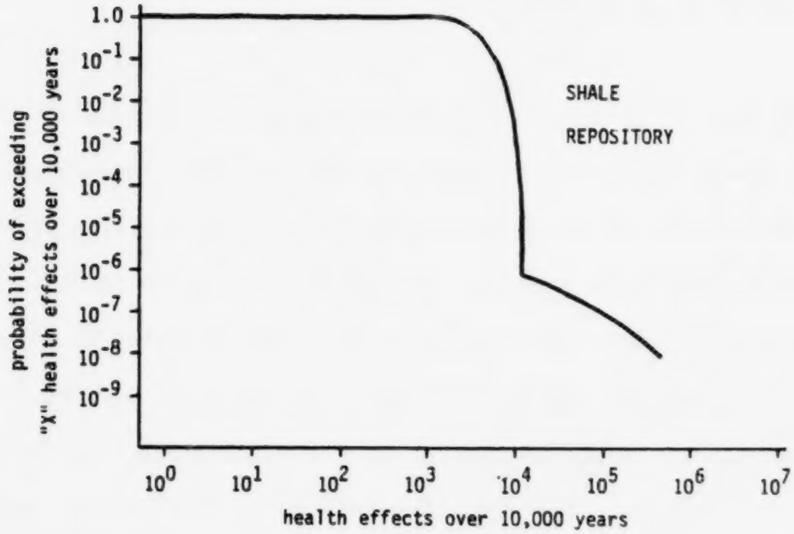


Figure 7-2: COMPLEMENTARY CUMULATIVE DISTRIBUTION FUNCTIONS
(Basalt and Shale)





in Table 7-4. The contributions of the various radionuclides for the more important events are presented in Table 7-5. The expected genetic effects for each repository are also shown in Table 7-4; however, these are much less than the somatic effects and will not be discussed further. Figure 7-3 compares the total somatic effects for each of the reference repositories, and Figures 7-4 and 7-5 depict the consquences and risks from the various events for the bedded salt, granite, basalt, and shale repositories.

In our tables, several significant figures are shown to facilitate itemizing and comparing the risks from different events and radionuclides. This is done strictly for convenience, we do not mean to imply that these estimates are that precise--certainly no more than one significant figure is meaningful in an absolute sense.

Each type of reference salt repository would cause about 200 health effects, almost all of them premature cancer deaths. Nearly all of these come from releases of americium-243 and 241 due to drilling events which hit contaminated brine pockets. The reference granite repository would cause about 800 health effects, which are also dominated by releases of americium-243 and 241 due to drilling. For the other hard rock repositories, the risks are considerably larger: about 4500 for basalt and about 7500 for shale. For these two reference repositories, normal groundwater flow through bulk rock is a significant contributor to the total number of projected health effects.

Table 7-4

Expected Health Effects over 10,000 Years: Reference Cases

Event	Bedded Salt	Domed Salt	Granite	Basalt	Shale
SOMATIC EFFECTS BY EVENT:					
Normal Ground Water Flow	0	0	11	1,420	1,420
Drilling (misses canister)	181	124	747	2,960	5,910
Drilling (hits canister)	5	5	0.6	2	5
Faulting	0.007	0.1	0.1	3	0.1
Breccia Pipe	0.001	-	-	-	-
Meteorite	0.003	0.003	0.003	0.003	0.003
Volcano	0.03	0.03	0.03	0.2	0.03
TOTAL SOMATIC EFFECTS:	186	129	760	4,390	7,340
TOTAL GENETIC EFFECTS:	2	2	13	153	200

Table 7-5

Expected Health Effects over 10,000 Years by Radionuclide: Reference Cases

Event	Nuclide	Bedded Salt	Domed Salt	Granite	Basalt	Shale
Normal Ground Water Flow	Sn-126	-	-	5.8	954	954
	C- 14	-	-	4.7	399	399
	Cs-135	-	-	0.6	47	47
	I-129	-	-	0.3	23	23
	Tc- 99	-	-	-	0.3	0.3
	TOTAL	-	-	11	1,420	1,420
Drilling (misses canister)	Am-243	103	69	671	2,650	5,290
	Am-241	78	55	75	304	607
	Sn-126	-	-	2	7	14
	TOTAL	181	124	747	2,960	5,910
Drilling (hits canister)	Am-241	1.6	1.6	0.2	0.8	1.6
	Pu-239	1.1	1.1	0.1	0.5	1.1
	Pu-240	1.1	1.1	0.1	0.5	1.1
	Am-243	0.8	0.8	0.1	0.4	0.8
	TOTAL	5	5	0.6	2	5
Faulting	C- 14	0.003	0.05	0.07	1.6	0.07
	Sn-126	0.003	0.04	0.04	1.1	0.04
	Cs-135	0.0005	0.007	0.01	0.2	0.01
	I-129	0.0002	0.004	0.005	0.1	0.005
	Tc- 99	0.0002	0.003	0.0003	0.006	0.0002
	TOTAL	0.007	0.1	0.12	3.1	0.12
TOTAL	Am-243	104	70	671	2,650	5,290
	Am-241	79	57	75	305	609
	Sn-126	0.02	0.05	7.6	959	965
	C- 14	0.005	0.05	4.8	401	399
	others	2.4	2.4	1.2	73	74
	TOTAL	186	129	760	4,390	7,340

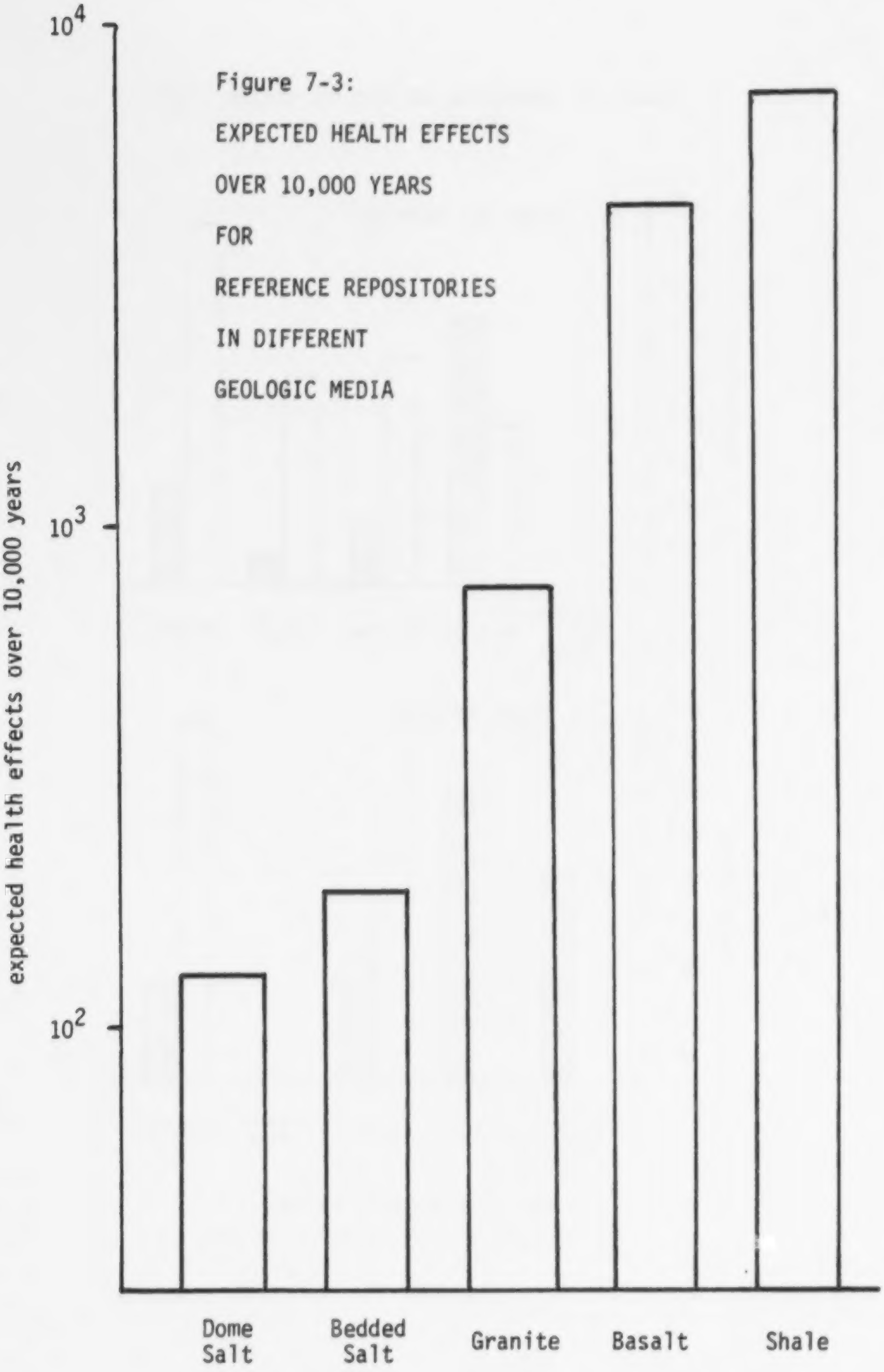


Figure 7-3:
EXPECTED HEALTH EFFECTS
OVER 10,000 YEARS
FOR
REFERENCE REPOSITORIES
IN DIFFERENT
GEOLOGIC MEDIA

Figure 7-4: CONSEQUENCES AND RISKS FOR DIFFERENT EVENTS (Bedded Salt and Granite)

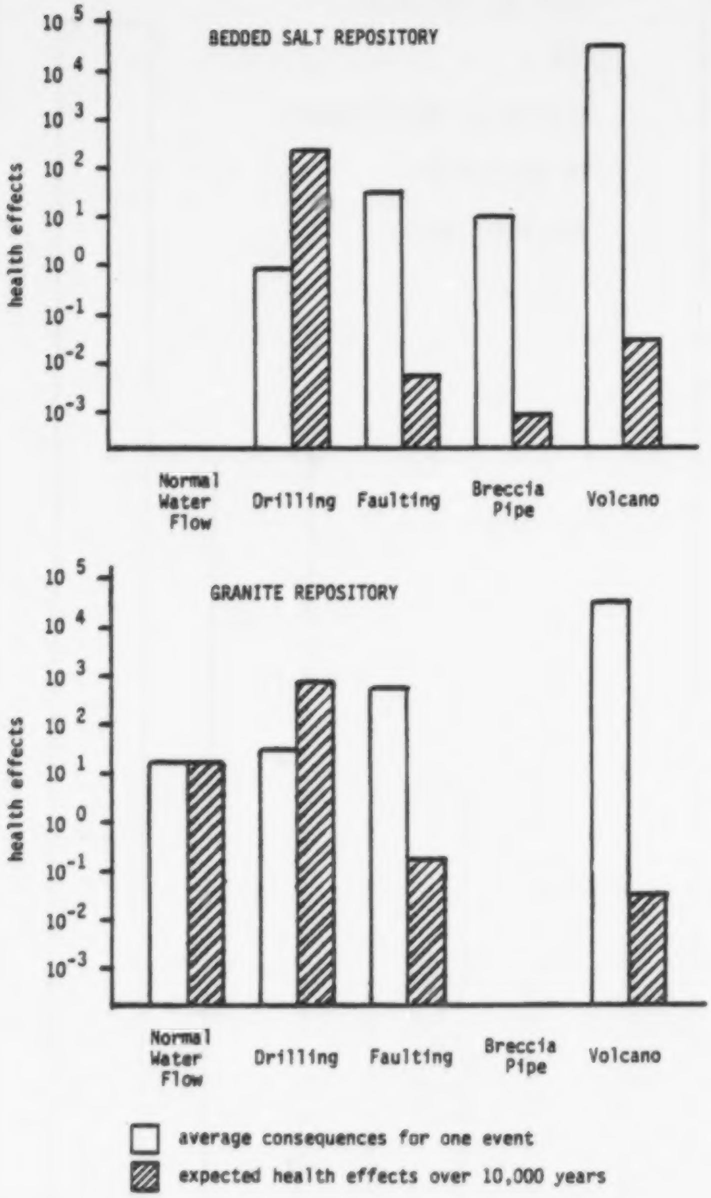
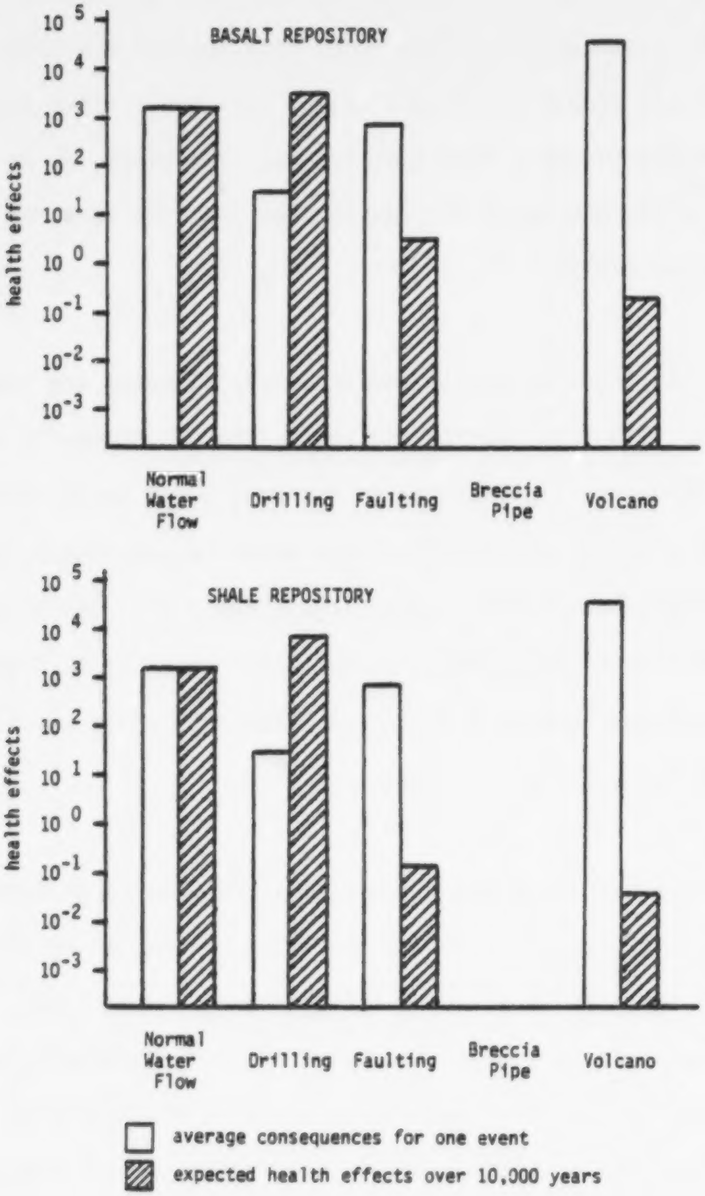


Figure 7-5: CONSEQUENCES AND RISKS FOR DIFFERENT EVENTS
(Basalt and Shale)



As Table 7-4 shows, only two types of events contribute significantly to the risks from the reference repositories: normal groundwater flow and intrusion by drilling that contacts contaminated groundwater in the repository. Although the consequences from some of the other events can be large, their probabilities are so low that their risks are always small relative to the two most important events. Therefore, as we compare the risks from different types of repositories, we only consider the risks from these two events.

The risks from the basalt and shale repositories are considerably larger than those from granite and salt. This is primarily due to much greater groundwater availability in the basalt and shale reference sites. The granite site has relatively little water because there is no underlying aquifer and the granite itself has a very low permeability; both factors limit the recharge rate. Water movement is limited at the salt sites because the salt will creep back into voids and fractures and shut off pathways for water flow.

The risks for the granite repository are also lower than those for basalt or shale because we assume that human intrusion by drilling is much less likely for granite than for these other two rock types. A different factor accounts for the small intrusion risks for the salt repositories. Although the future intrusion rate for salt is assumed to be among the highest, there is so little water in the reference salt repositories that our assumed radionuclide solubility limits greatly reduce the potential releases from intrusion.

The two americium isotopes dominate the risks from releases to land surface for two reasons: (1) they cause the most health effects per curie released to the environment, and (2) the other alpha-emitting radionuclides are restricted by much lower solubility limits. The relatively high retardation factor for americium prevents these isotopes from contributing to the risks due to normal groundwater flow, however.

Tin-126 and carbon-14 are the dominant radionuclides for the groundwater flow pathway. Thus, for the salt and granite reference cases, the americium isotopes contribute almost all of the risks because releases to the land surface from intrusion dominate the results. For the basalt and shale cases, tin-126 and carbon-14 are also significant because normal groundwater flow causes a substantial part of the overall risks.

7.5 Effects of Different Assumptions

We performed a wide variety of sensitivity analyses to evaluate the effects of different assumptions about the various parts of the repository systems. We only considered bedded salt, granite and basalt in these sensitivity analyses because our analyses for domed salt are very similar to bedded salt and those for shale are similar to basalt. Our sensitivity analyses address different waste form release rates, canister lifetimes, solubility limits, retardation factors, event probabilities, and integration periods.

7.5.1 Different Waste Form Release Rates and Canister Lifetimes

Figure 7-6 shows how the expected health effects vary with different waste form release rates. The risks increase in direct proportion to the increased release rate with two exceptions: (1) the risks for the bedded salt repository do not increase much above those for a 10^{-5} parts per year (ppy) release rate because of the solubility limits on the americium isotopes, and (2) risks for the hard rock repositories do not increase much beyond a 10^{-3} ppy rate because there is no more waste to dissolve during the 10,000 year period of interest. Above this release rate, dissolving the waste even faster has relatively little effect on the overall results.

Figure 7-7 shows how expected health effects vary with different canister lifetimes. Over the range we considered, canister lifetime has much less effect on the results than the waste form release rate. The primary effect of larger canister lifetimes is to shorten the period over which risks from human intrusion and normal groundwater flow can occur.

Finally, to study the effect of varying both waste form release rate and canister lifetime simultaneously, we did a series of parametric analyses for the granite repository. These results are displayed in Figures 7-8 and 7-9, and they reinforce the observation that release rates have more effect on the overall risks than canister lifetimes.

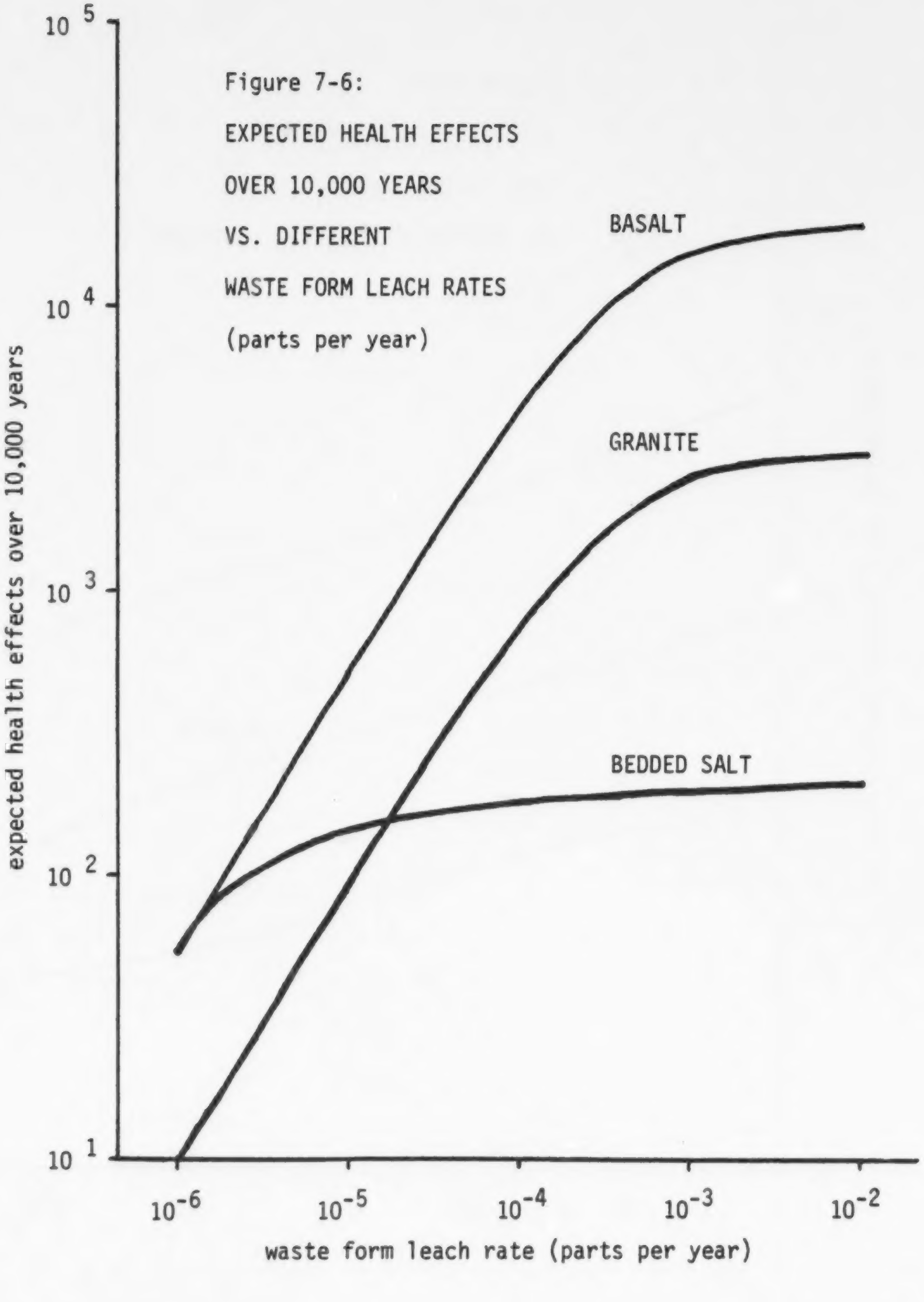


Figure 7-6:
EXPECTED HEALTH EFFECTS
OVER 10,000 YEARS
VS. DIFFERENT
WASTE FORM LEACH RATES
(parts per year)

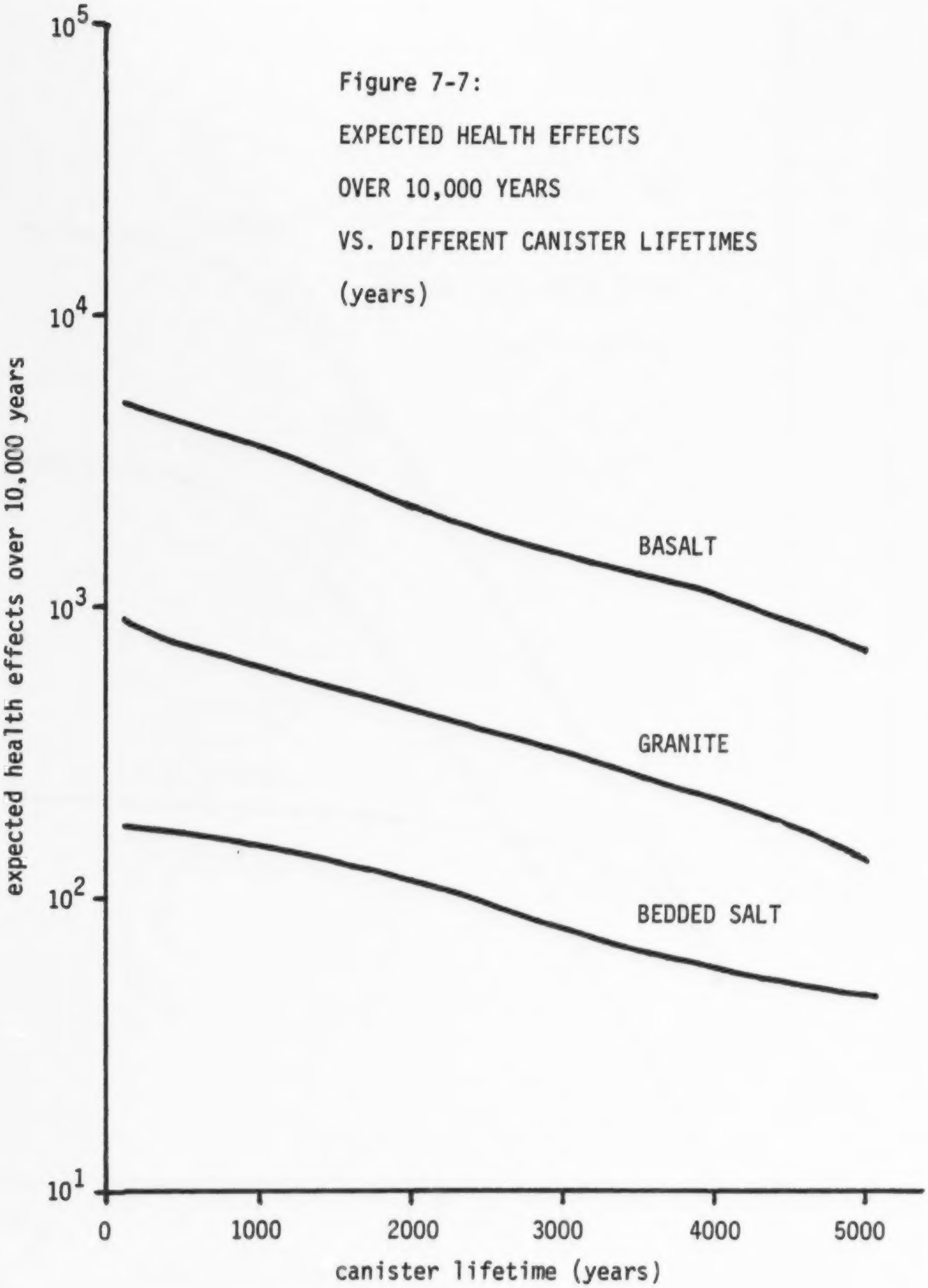


Figure 7-7:

EXPECTED HEALTH EFFECTS

OVER 10,000 YEARS

VS. DIFFERENT CANISTER LIFETIMES

(years)

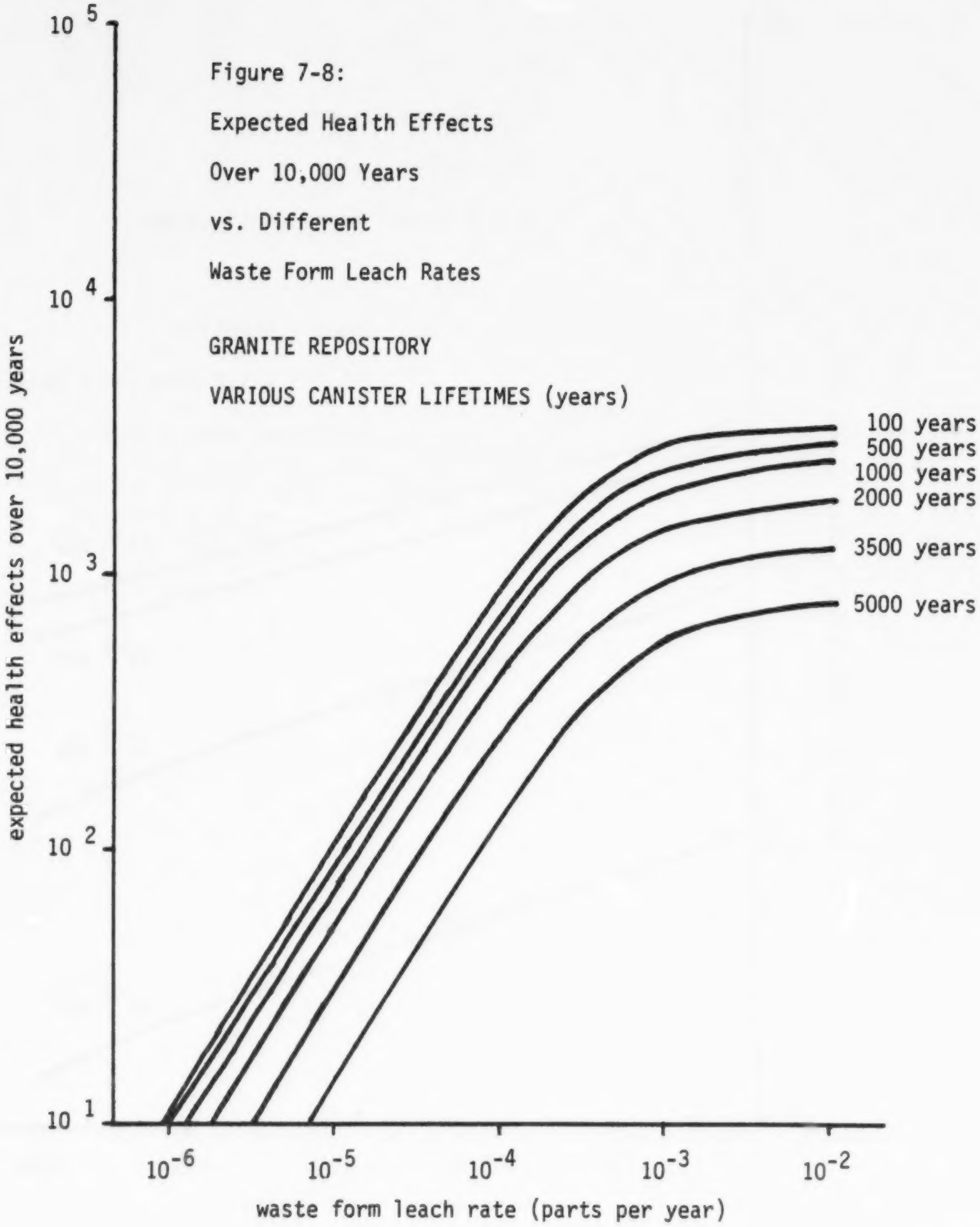


Figure 7-8:
Expected Health Effects
Over 10,000 Years
vs. Different
Waste Form Leach Rates

GRANITE REPOSITORY
VARIOUS CANISTER LIFETIMES (years)

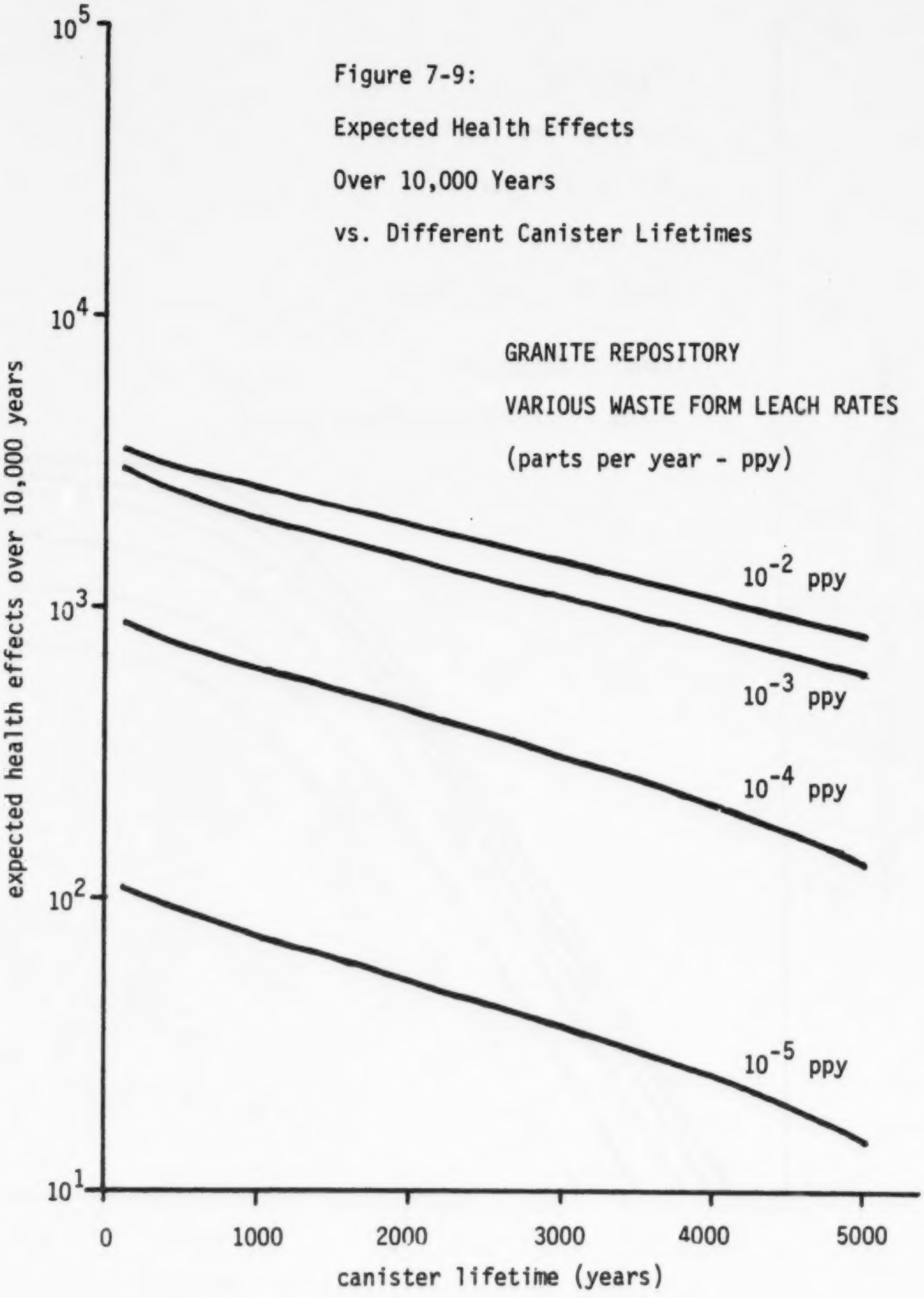


Figure 7-9:
Expected Health Effects
Over 10,000 Years
vs. Different Canister Lifetimes

7.5.2 Solubility Limits

We analyzed the effect of our solubility limits (Table 4-1) by repeating our analyses without any solubility limits: any radionuclides that could be removed from the waste form would directly enter the groundwater. Table 7-6 shows these results.

Removing the solubility limits increases the risks substantially for all of the repository types. However, the increase is most dramatic (almost two orders of magnitude) for the salt repository. As noted earlier, very little water enters the reference salt repository, which makes the solubility limits (particularly the limits on plutonium and americium) very important factors in limiting the risks from a salt repository.

We also looked at the importance of waste form release rate and canister lifetime on a salt repository without solubility limits. These results are displayed in Figures 7-10 and 7-11, and they tend to reinforce some previous observations: (1) without the effects of solubility limits, risks increase in direct proportion to the release rate up until a release rate of about 10^{-3} parts per year, and (2) reducing the release rate is a more effective way to reduce risks than improving canister lifetime, particularly if there are large uncertainties about the solubilities of the radioactive wastes in the groundwater.

Table 7-6

Expected Health Effects over 10,000 Years:

No Radionuclide Solubility Limits

Event	Bedded Salt	Granite	Basalt
Normal Ground Water Flow	0	14	1,640
Drilling (misses canister)	14,700	2,770	11,000
Drilling (hits canister)	5	0.6	2
Faulting	0.009	0.2	4
Breccia Pipe	0.001	-	-
Meteorite	0.003	0.003	0.003
Volcano	0.03	0.03	0.2
TOTAL SOMATIC EFFECTS:	14,700	2,790	12,600

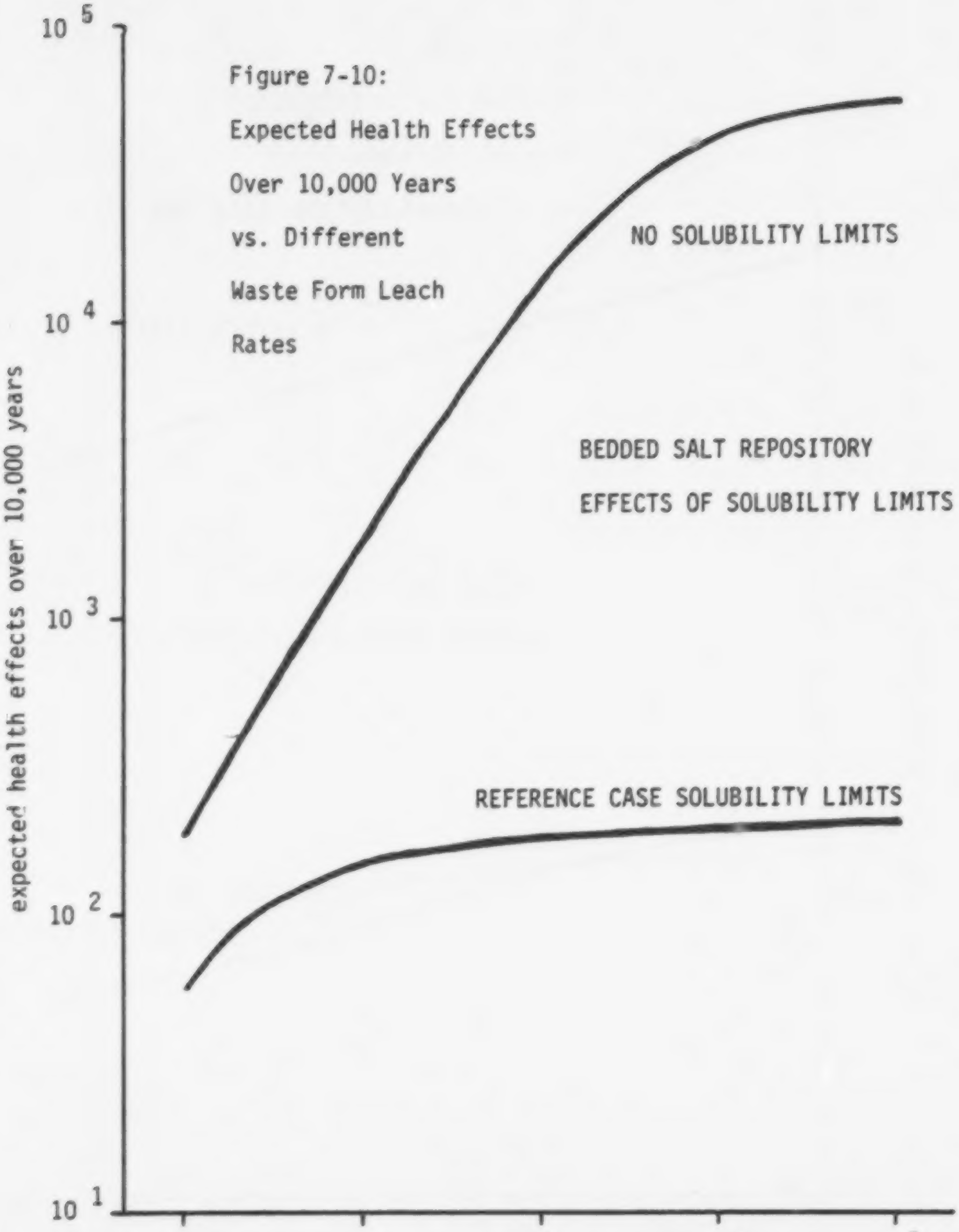


Figure 7-10: Expected Health Effects Over 10,000 Years vs. Different Waste Form Leach Rates

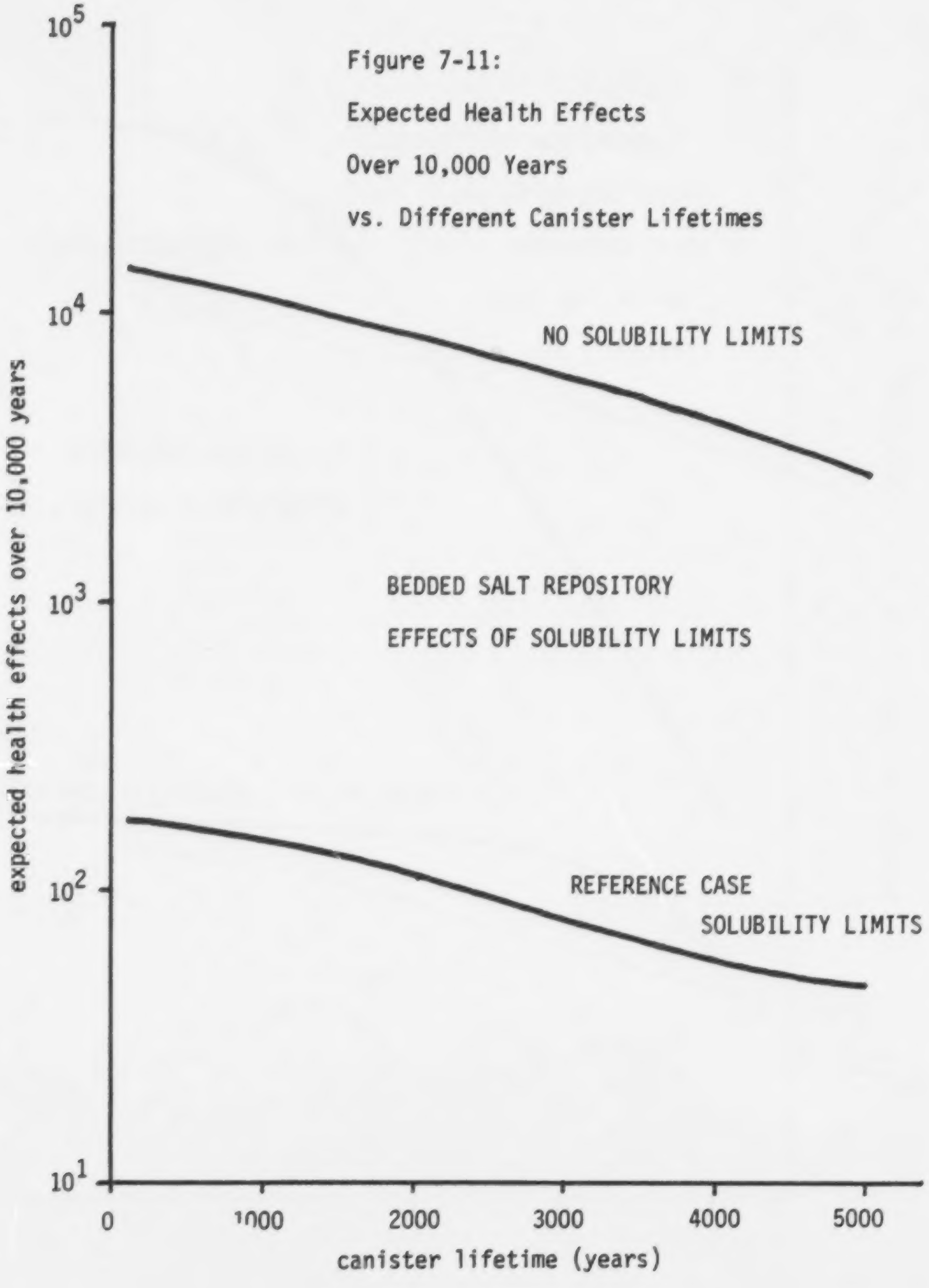


Figure 7-11:
Expected Health Effects
Over 10,000 Years
vs. Different Canister Lifetimes

7.5.3 Different Retardation Factors

We evaluated the effects of different retardation factors by performing two additional analyses. In one case, we replaced our reference case retardation factors with retardation factors reported by Denham, et al. (DE 73), which generally assume a greater level of geochemical interaction with the surrounding rock formations (Table 4-1 lists both sets of factors). In the other case, we assumed that no retardation took place and that all radionuclides moved with the same velocity as the groundwater (although dissolution in the groundwater was still subject to our solubility limits). Tables 7-7 and 7-8 display the results of these two analyses.

The changes in retardation factors affect only those events which involve significant groundwater flow pathways, such as faulting, breccia pipe formation, and, of course, the normal groundwater flow expected in the hardrock repositories. Use of the Denham factors generally reduces these risks by only a little more than an order of magnitude, even though many of the Denham factors assume up to a hundred times greater retardation. This reduction in risk is relatively small because, for our reference geologic settings, a retardation factor of about 15 is sufficient to prevent a radionuclide from ever reaching the accessible environment through groundwater flow in less than 10,000 years. Increasing a retardation factor from 100 to 10,000 has no effect on our analysis.

Table 7-7

Expected Health Effects over 10,000 Years: No Geochemical Retardation

Event	Bedded Salt	Granite	Basalt
Normal Ground Water Flow	0	36,800	5,200,000
Drilling (misses canister)	181	747	2,960
Drilling (hits canister)	5	0.6	2
Faulting	27	458	11,400
Breccia Pipe	4	-	-
Meteorite	0.003	0.003	0.003
Volcano	0.03	0.03	0.2
TOTAL SOMATIC EFFECTS:	217	38,000	5,210,000

Table 7-8

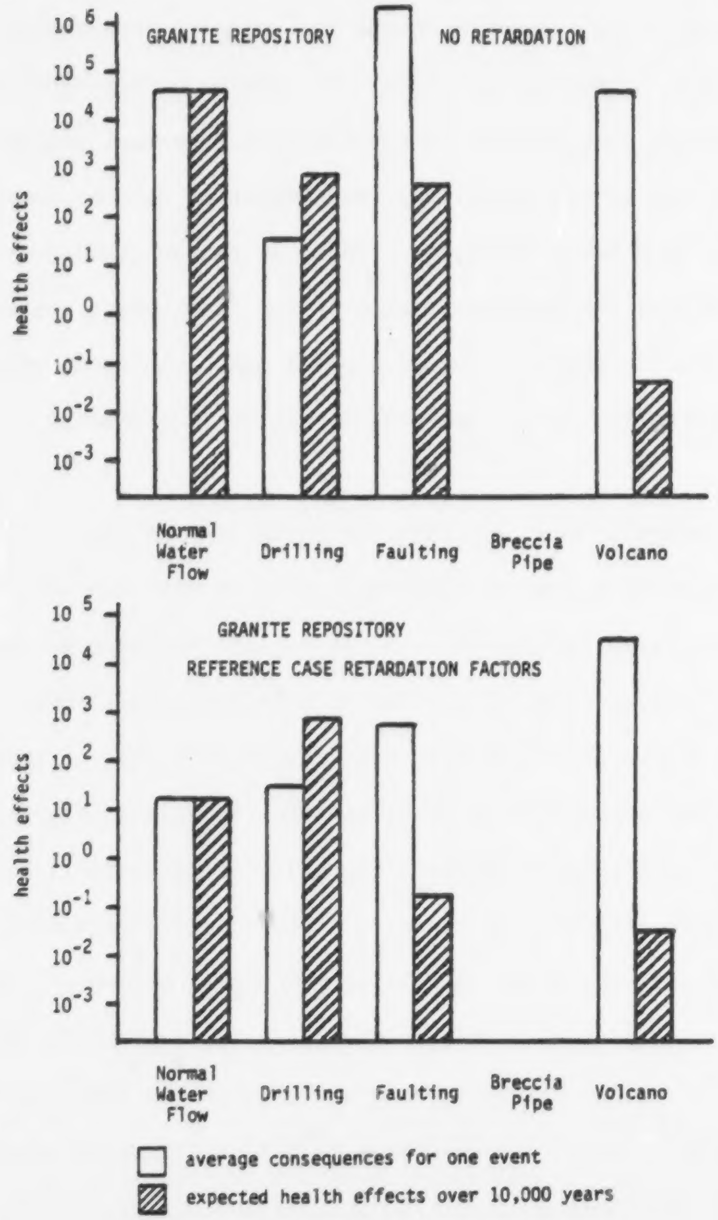
Expected Health Effects over 10,000 Years: Denham Retardation Factors

Event	Bedded Salt	Granite	Basalt
Normal Ground Water Flow	0	0.7	87
Drilling (misses canister)	181	747	2,960
Drilling (hits canister)	5	0.6	2
Faulting	0.006	0.008	0.2
Breccia Pipe	0.0002	-	-
Meteorite	0.003	0.003	0.003
Volcano	0.03	0.03	0.2
TOTAL SOMATIC EFFECTS:	186	749	3,050

On the other hand, assuming no retardation dramatically increases the risks for events involving groundwater flow. As shown by Table 7-7 and Figure 7-12, these increases change the relative importance of different events in the overall risks. For the hard rock repositories, normal groundwater flow becomes by far the most important source of releases. For the basalt repository, even faulting becomes considerably more important than human intrusion. Thus, it can be concluded that human intrusion dominates the overall risks only for cases where the site geochemistry and the chemical composition of the waste form insure substantial protection by the geologic formations surrounding a repository.

We also looked at the importance of waste form release rate and canister lifetime on a granite repository with no retardation. These results are displayed in Figures 7-13 and 7-14. The shape of the curve for different release rates is similar to previous curves, but substantially higher at all release rates due to the lack of geochemical retardation. The curve for different canister lifetimes (Figure 7-14) leads to a new conclusion, however. Improving the canister lifetime is considerably more effective in reducing risks for this case than for others. In effect, the delay in releases through groundwater caused by a longer-lived canister can substitute for the delay that would otherwise be provided by geochemical retardation. In fact, for the granite repository, where groundwater travel times increase significantly as the waste cools down, canister lifetimes greater than 5,000 years can completely compensate for a lack of geochemical retardation.

Figure 7-12: Consequences and Risks for Different Events
(EFFECTS OF RETARDATION FACTORS)



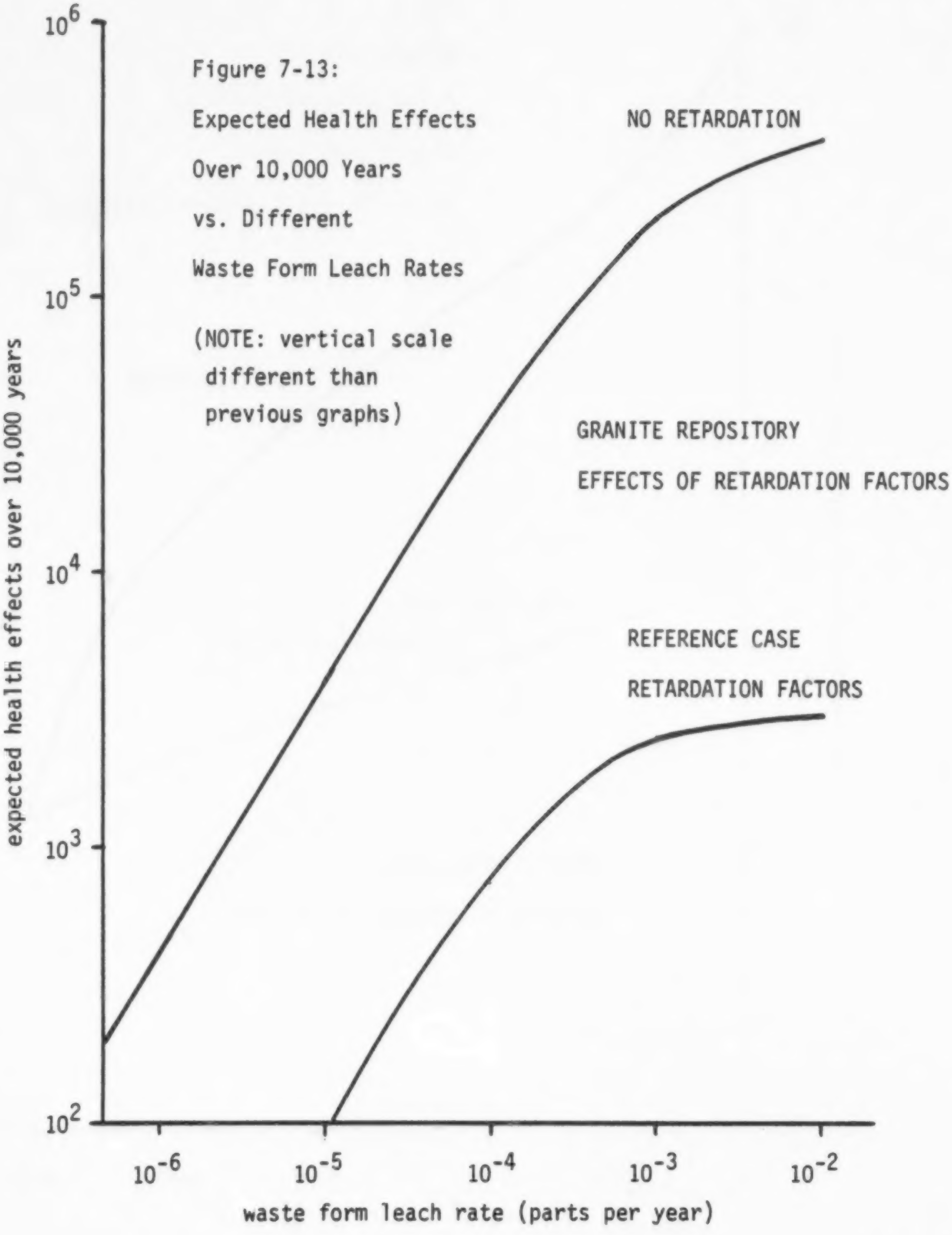


Figure 7-13:
Expected Health Effects
Over 10,000 Years
vs. Different
Waste Form Leach Rates

(NOTE: vertical scale
different than
previous graphs)

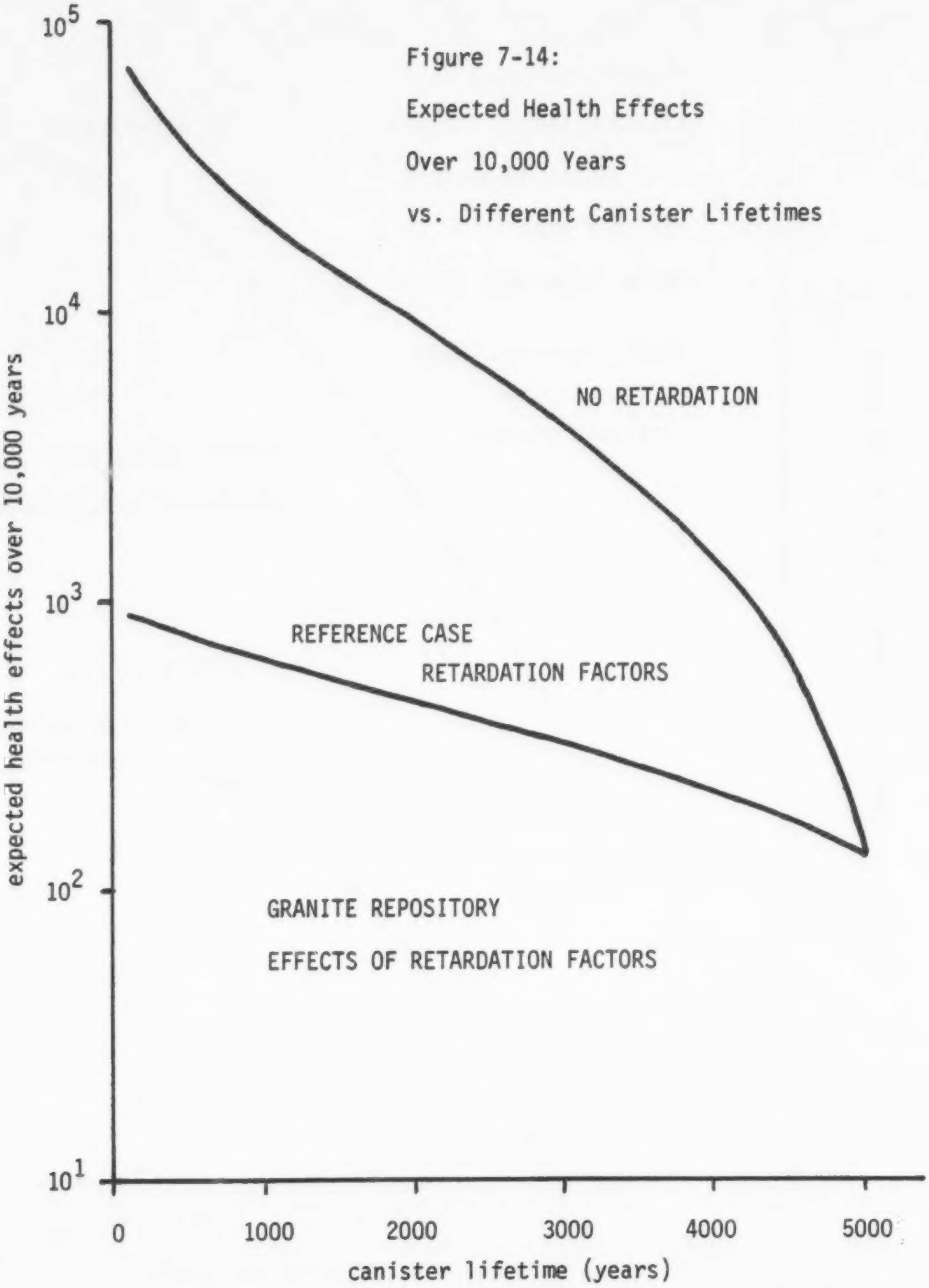


Figure 7-14:

Expected Health Effects

Over 10,000 Years

vs. Different Canister Lifetimes

7.5.4 Summary of the Effects of Geochemical Factors

Table 7-9 summarizes the overall risks from our examination of the importance of solubility limits and retardation factors. Solubility limits are more important for our reference salt repositories, where little groundwater should enter the system and where releases caused by human intrusion dominate the risks. Retardation factors are more important for the hard rock repositories, where releases through groundwater flow pathways are much more significant.

We also include in Table 7-9 the results if neither solubility limits or retardation factors are considered. These analyses indicate that, even without any protection from site geochemistry, there is a substantial difference in overall risks between the basalt case and the salt and granite cases. The additional protection provided by the reference salt repository occurs (1) because there is no "normal" groundwater flow through the salt itself and (2) because salt creep will tend to compress the repository backfill and isolate the waste canisters from each other, thus reducing the source term available for localized disruptive events. The additional protection provided by the reference granite repository occurs because there is no underlying aquifer to maintain an upward hydraulic gradient as the wastes cool; thus, the driving force to remove dissolved wastes from the repository is much reduced after about 1000 years. The basalt reference case has neither of these advantages.

Table 7-9

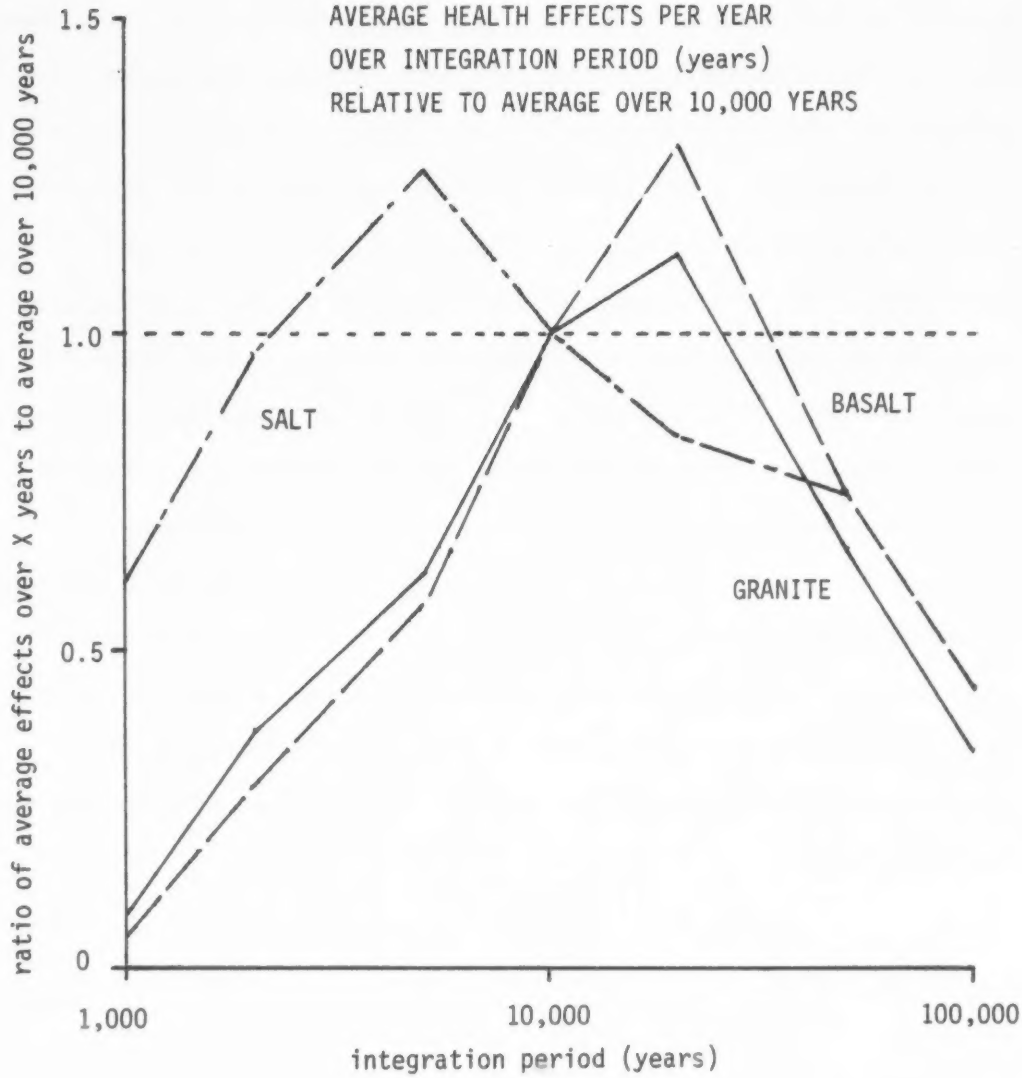
Expected Health Effects over 10,000 Years: Effects of Different Geochemical Factors

Event	Bedded Salt	Granite	Basalt
Reference Case	186	760	4,390
Denham Retardation Factors	186	749	3,050
No Retardation	217	38,000	5,210,000
No Solubility Limits	14,700	2,790	12,600
No Solubility Limits AND No Retardation	14,800	68,500	7,570,000

7.5.5 Different Integration Periods

We also performed a number of analyses considering integration periods other than 10,000 years. We wanted to know if stopping our analysis at 10,000 years could substantially misrepresent the risks from our reference repositories. To do this, we considered the average risk per year for several integration periods. Figure 7-15 presents these results, normalized to the average risk per year over 10,000 years, for each of the three geologic media. Although 10,000 years does not correspond to the largest average risk for any of the media, the average risks for the other periods we studied were never more than 30 percent higher than those at 10,000 years. Our results for the longer integration times, those approaching 100,000 years, may be somewhat underestimated because our models do not consider in-growth of Ra-226 and other radionuclides in the long-lived decay chains stemming from the uranium and plutonium in the wastes. However, we believe that the underestimates would be quite small for our reference repositories. Figure 7-15 also shows that cutting off the analyses at 1000 years would result in substantial underestimates of the average risks, particularly for the hard rock repositories.

Figure 7-15:
AVERAGE HEALTH EFFECTS PER YEAR
OVER INTEGRATION PERIOD (years)
RELATIVE TO AVERAGE OVER 10,000 YEARS



7.5.6 Higher Probabilities

We considered uncertainties in the probabilities of releases by repeating our analyses with a set of higher event probabilities that was developed by Arthur D. Little, Inc. (ADL 79d). These higher probabilities are discussed in Appendix D. As shown in Table 7-10, the expected health effects are higher, particularly for human intrusion by drilling. However, they are not dramatically higher. The increases in risks from making much more conservative assumptions about event probabilities are much smaller than the increases caused by making more conservative assumptions about other aspects of our analyses.

Table 7-10

Expected Health Effects over 10,000 Years: Higher Event Probabilities

Event	Bedded Salt	Domed Salt	Granite	Basalt	Shale
SOMATIC EFFECTS BY EVENT:					
Normal Ground Water Flow	0	0	11	1,420	1,420
Drilling (misses canister)	453	310	5980	14,800	14,800
Drilling (hits canister)	12	12	5	12	12
Faulting	0.07	17	50	60	1
Breccia Pipe	0.1	-	-	-	-
Meteorite	0.003	0.003	0.003	0.003	0.003
Volcano	3	0.03	3	3	3
TOTAL SOMATIC EFFECTS:	468	339	6050	16,300	16,200

Appendix A

REPOSITORY RADIONUCLIDE INVENTORY

For our analysis of reference waste repositories, we have developed a reference radionuclide inventory that is representative of the contents of commercial radioactive waste that will be disposed in high-level waste repositories. Projections of non-commercial waste comprise only a small fraction of the total. The waste will either be in the form of unreprocessed spent fuel from commercial reactors, or waste left from reprocessing spent fuel to recover uranium and/or plutonium. Our reference waste only includes spent fuel, which contains more isotopes (per metric ton of heavy metal charged to the reactor) that are important--because of their long half-lives, ease of environmental transport, or biological significance--than does the waste from reprocessing spent fuel.

Arthur D. Little, Inc. (ADL) has provided us with a detailed analysis of the characteristics of high-level wastes (ADL 79a). ADL used the ORIGEN computer program (BE 73) with an updated set of actinide data to generate radioisotopic inventories for pressurized water reactor fuel with a discharge exposure of 33,000 MWd/MTHM. Three alternative light water reactor (LWR) fuel cycles were considered:

1. "throwaway" fuel cycle---spent fuel, no reprocessing
2. urainum only recycle
3. uranium and plutionium recycle

Figures A-1 and A-2 compare the quantity of radioactivity (curies) of the three fuel cycles and their decay heat generation by graphically depicting the ORIGEN results. In terms of quantity of radioactivity,

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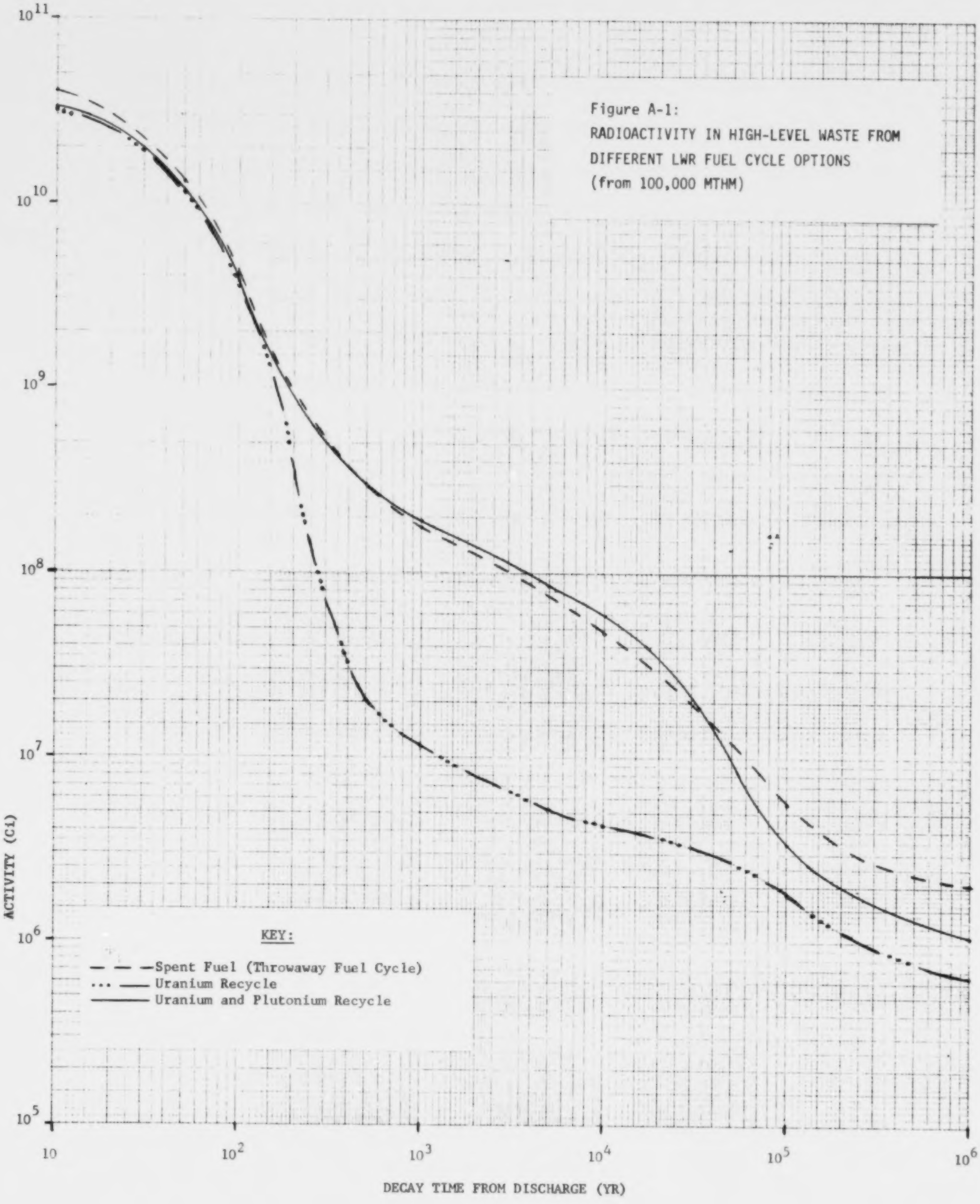

Figure A-1:
RADIOACTIVITY IN HIGH-LEVEL WASTE FROM DIFFERENT LWR FUEL CYCLE OPTIONS
(from 100,000 MTHM)

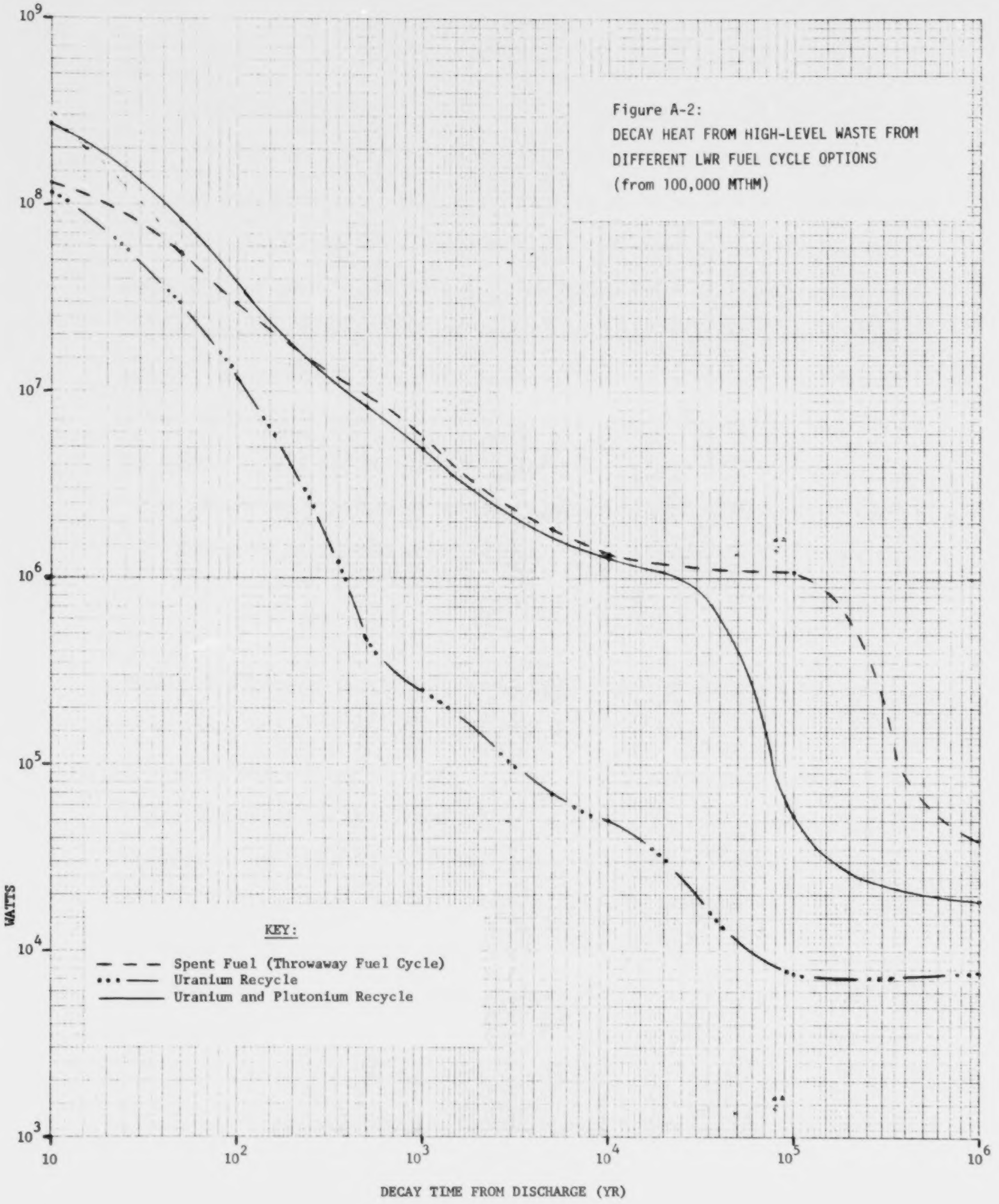

Figure A-2:
DECAY HEAT FROM HIGH-LEVEL WASTE FROM DIFFERENT LWR FUEL CYCLE OPTIONS (from 100,000 MTHM)

all three options are comparable for about the first thousand years. After a thousand years, the high-level waste activity from the uranium-only recycle waste is generaly much lower. As indicated in Figure A-2, the decay heat from the uranium-only recycle is also much lower than either the "throwaway" fuel cycle or the uranium and plutonium recycle wastes. Wastes from these latter two fuel cycles generate a comparable amount of decay heat for about the first 10,000 years. Beyond 10,000 years, the heat of the "throwaway" fuel is much higher than that of the uranium and plutonium recycle waste, because of the higher content of Pu-239 and Pu-240 in the "throwaway" fuel cycle wastes. Therefore, we have chosen the "throwaway" fuel cycle to characterize the reference inventory of high-level radioactive wastes.

An overall picture of the "throwaway" fuel cycle inventory is shown in Figure A-3 for a fuel charge of 100,000 MTHM, which is the quantity of waste we chose for our reference geologic repository. The two major types of radioactivity in spent fuel are the fission products, which dominate for about the first one hundred years, and the actinides, including their daughter radionuclides. A third, less significant, category of radioactivity is the fuel assembly structural components, which comprise only 0.1 to 1.0 percent of the total radioactivity in the repository at any given time.

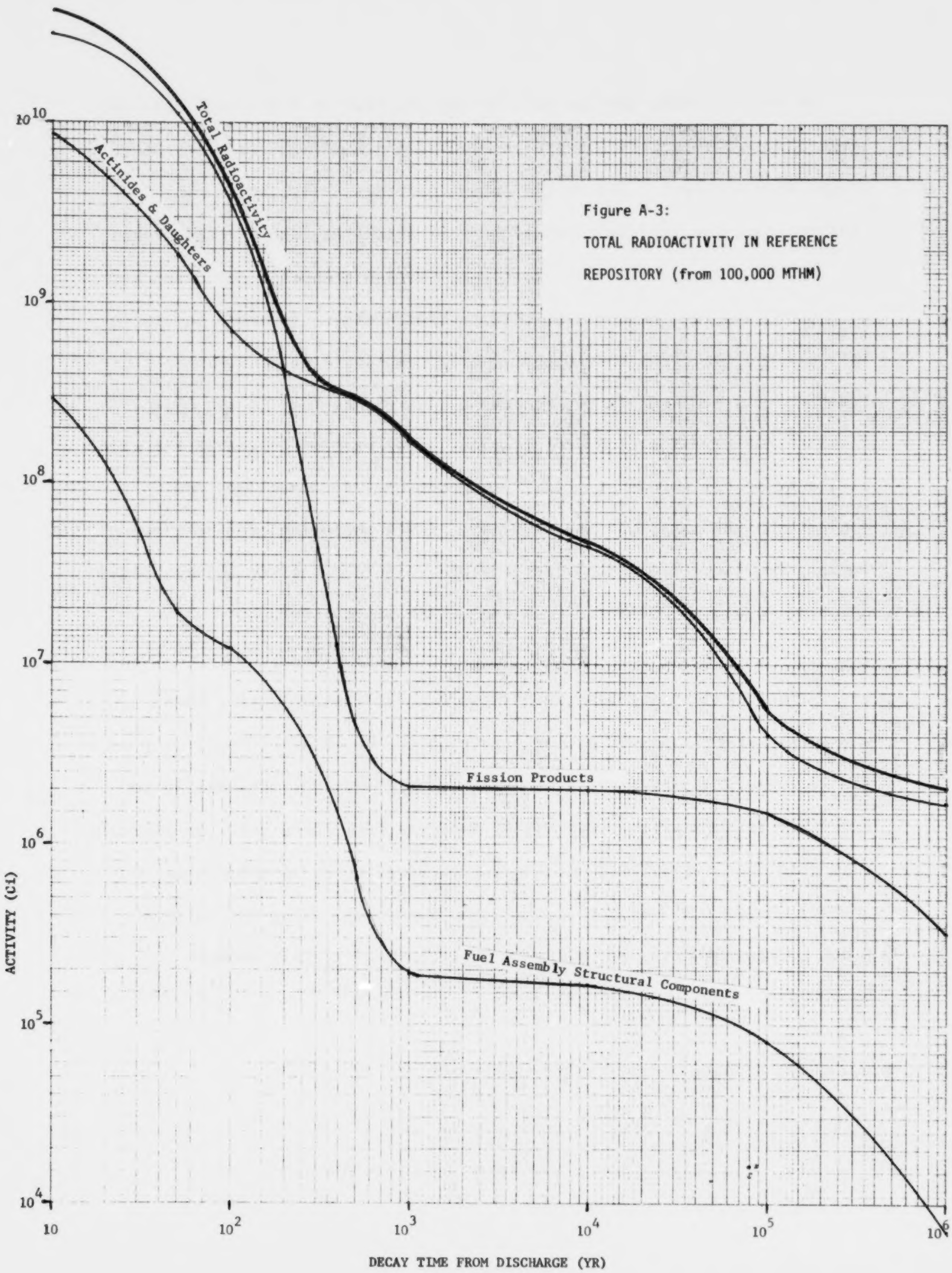

Figure A-3:
TOTAL RADIOACTIVITY IN REFERENCE
REPOSITORY (from 100,000 MTHM)

In order to make the analysis of the disposal of high-level and long lived radioactive wastes easier, we developed a modified inventory based on the ORIGEN output. The ORIGEN output provides a listing of the radionuclides for various times after fuel discharge, and it categorizes the inventory by type of activity (i.e., fission products, actinides and daughters, and fuel assembly structural components). In order to ensure that all radionuclides that significantly contribute to total radioactivity are considered, we made a list of the five to ten most abundant radionuclides for various times after reactor discharge for each of the major categories of activity. Additional radionuclides are included on the basis of long half-life, small geological retardation factor, and large biological significance. Table 2-1 lists the resulting principal isotopes extracted from the ORIGEN program output.

Since the activity associated with the fuel assembly structural components comprises only a small fraction of the total radioactivity in the repository at any given time, this category was not included in our reference inventory; therefore it is excluded from Table 2-1. We should also note that the estimate of the C-14 production as an activation product in the fuel has been calculated separately, using the value of 0.561 Ci/MTU (DA 77). For our reference repository, this amounts to 56,100 Ci of C-14.

Comparing our reference inventory with the ORIGEN output, our list comprises 95 to 99 percent of the total curies of all the radionuclides for almost all periods of interest. Figure A-4 depicts the radionuclide inventory in a reference repository. For the first hundred years or so, the fission product inventory is dominated by the Sr-90/Y-90 and the Cs-137/Ba-137m decay chains. Beyond 600 years, Tc-99 dominates until almost a million years. For the puposes of the analytical model used in this report, the fission product inventories listed in Table 2-1 for ten years after fuel discharge are used as the starting point; these radionuclides inventories are taken directly from the ORIGEN program output. For most fission product radionuclides, the inventory at any subsequent time may be calculated by applying the appropriate radiological half-life. However, for those radionuclides listed in Table 2-1 involved in fission product decay chains--the Cs-137/Ba-137m chain, the Zr-93/Nb-93m chain, and the Sn-126/Sb-126m/Sb-126 chain---we assume that the activity of the daughters and parents are equal. Our assumption is slightly conservative, as may be seen by examining the activities of the decay chains in Table 2-1.

Because of long decay chains containing many radionuclides with relatively long half-lives, the long-term behavior of individual actinide and daughter isotopes is much more complicated. The ORIGEN program uses Bateman equations to describe the ingrowth and decay of these isotopes. We simplified the model for the actinide and daughter radionuclide source

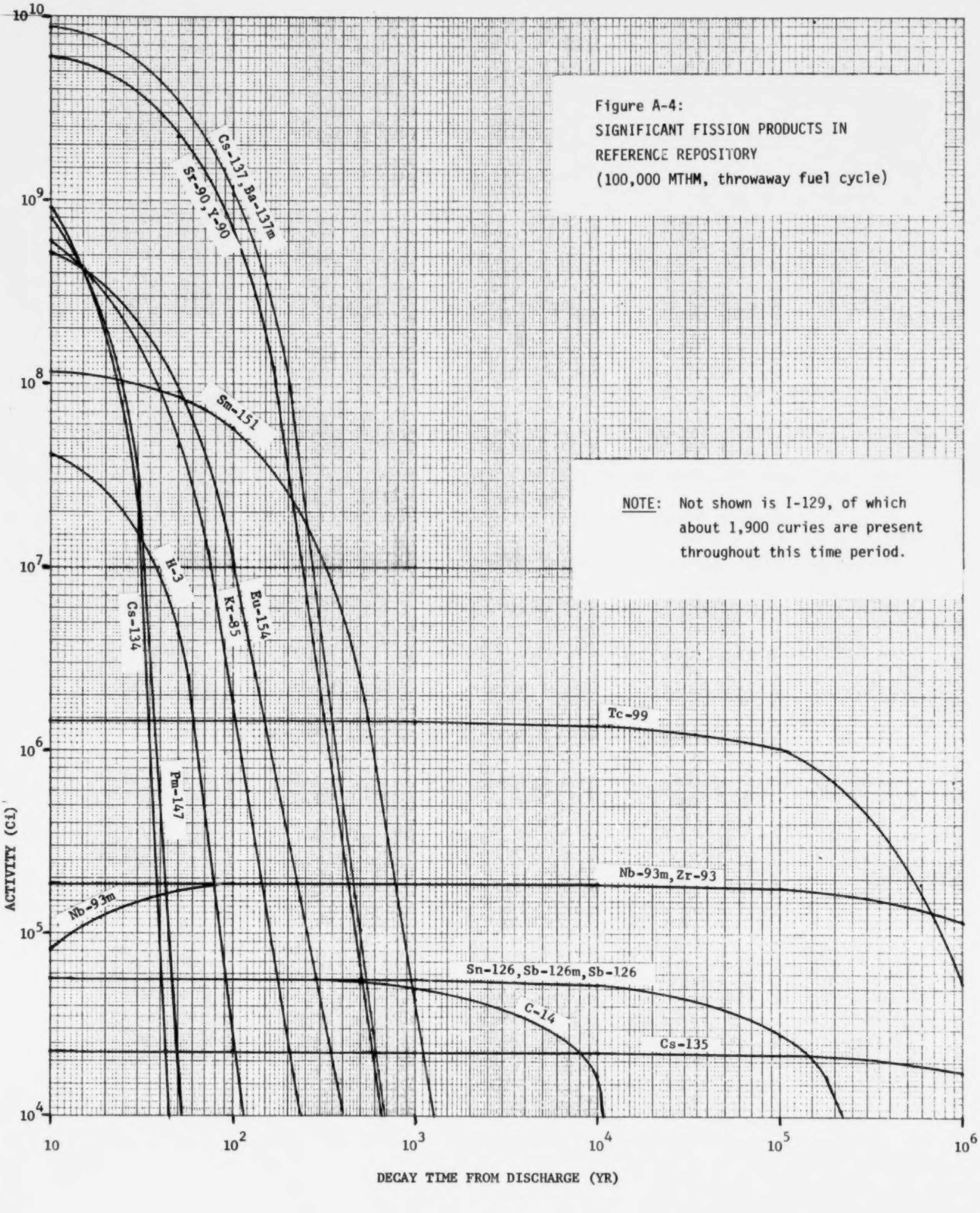

Figure A-4:
SIGNIFICANT FISSION PRODUCTS IN REFERENCE REPOSITORY
(100,000 MTHM, throwaway fuel cycle)

NOTE: Not shown is I-129, of which about 1,900 curies are present throughout this time period.

term in order to provide a more manageable model. First, the principal actinide and daughter radionuclides listed in Table 2-1 have been broken down into respective decay chains.

1. Am-243--> Np-239--> Pu-239--> U-235
2. Pu-241--> Am-241--> Np-237--> Pa-233
3. Pu-238--> U-234---> Th-230--> Ra-226
4. Cm-244--> Pu-240

Of the four major decay chains, only the Pu-241 chain has a parent isotope (Cm-245) that significantly contributes to the activity of the first member of the chain. Based on the ORIGEN output, the parent isotopes of Am-243, Pu-238, and Cm-244 all have lower activity levels compared to their respective daughters.

These four decay chains account for all of the principal isotopes in Table 2-1 except Pu-242. This isotope is formed by the decay of both Am-242 and Cm-246. The ORIGEN output shows that, upon discharge of the fuel from reactors, only very small quantities of Am-242 and Cm-246 are present relative to Pu-242. Therefore, Pu-242 is treated as decaying to U-238, ignoring any contribution from Am-242 and Cm-246.

In our simplified model for actinides and daughters, the radionuclides are treated in pairs. We assume radionuclide A, with an initial inventory A_0, decays into radionuclide B, which has an initial inventory B_o, and which concurrently decays according to its half-life. Therefore, the rate of change of the number of B atoms may be expressed as:

$$\frac{dB}{dt} = A\lambda_1 - B\lambda_2 \qquad \text{(A-1)}$$

where A and B are the number of atoms of A and B, respectively, at any time t, and λ_1 and λ_2 are the respective decay constants for A and B.

Since: $$A = A_o e^{-\lambda_1 t} \qquad \text{(A-2)}$$

equation A-1 may be rewritten as

$$\frac{dB}{dt} = \lambda_1 A_o e^{-\lambda_1 t} - \lambda_2 B \qquad \text{(A-3)}$$

The solution to this linear differential equation for B as a function of time, considering initial amounts of A and B (A_o and B_o respectively), is:

$$B = A_o\lambda_1 (e^{-\lambda_1 t} - e^{-\lambda_2 t})/(\lambda_2 - \lambda_1) + B_o e^{-\lambda_2 t} \qquad \text{(A-4)}$$

This equation describes the number of atoms of B at any time. A more convenient form expressed in terms of radioactivity may be achieved by multiplying both sides of equation A-4 by λ_2:

$$\text{activity of isotope B} = \lambda_2 B = \frac{\lambda_2}{\lambda_2 - \lambda_1} \lambda_1 A_o (e^{-\lambda_1 t} - e^{-\lambda_2 t}) + \lambda_2 B_o e^{-\lambda_2 t} \qquad \text{(A-5)}$$

Equation A-5 describes the activity of radionuclide B at any time, given initial activities of A and B. We used this equation to estimate the ingrowth and decay among the actinides and daughters in the four major decay chains listed above.

Figure A-5 illustrates the results of applying Equation A-5 to the decay chains for the principal actinides as compared to the ORIGEN output. Agreement for the principal radionuclides is such that differences between the two models is 10 percent or less; most results agree so well that it is impossible to detect the difference.

Presently, the decay chains leading to the buildup of Ra-226 have not been modeled or included in the results of this paper. These decay chains are very difficult to model for releases to an aquifer. Fortunately for the event times during a 10,000 year period, the buildup of Ra-226 does not seem to be very important. Generally two types of releases are analyzed in this report--direct releases to the air or land surface and long term releases through the aquifer pathway. All the direct releases occur during the 10,000 year time period. Thus, very little Ra-226 is released directly. The parent radionuclides of Ra-226 that are released directly are effectively removed from the accessible environment within a few hundred years after the release. The environmental "sinks" for these radionuclides are either the lower soil layers or the ocean sediments. These parent radionuclides are thus effectively removed from the environment prior to any signficant growth of Ra-226.

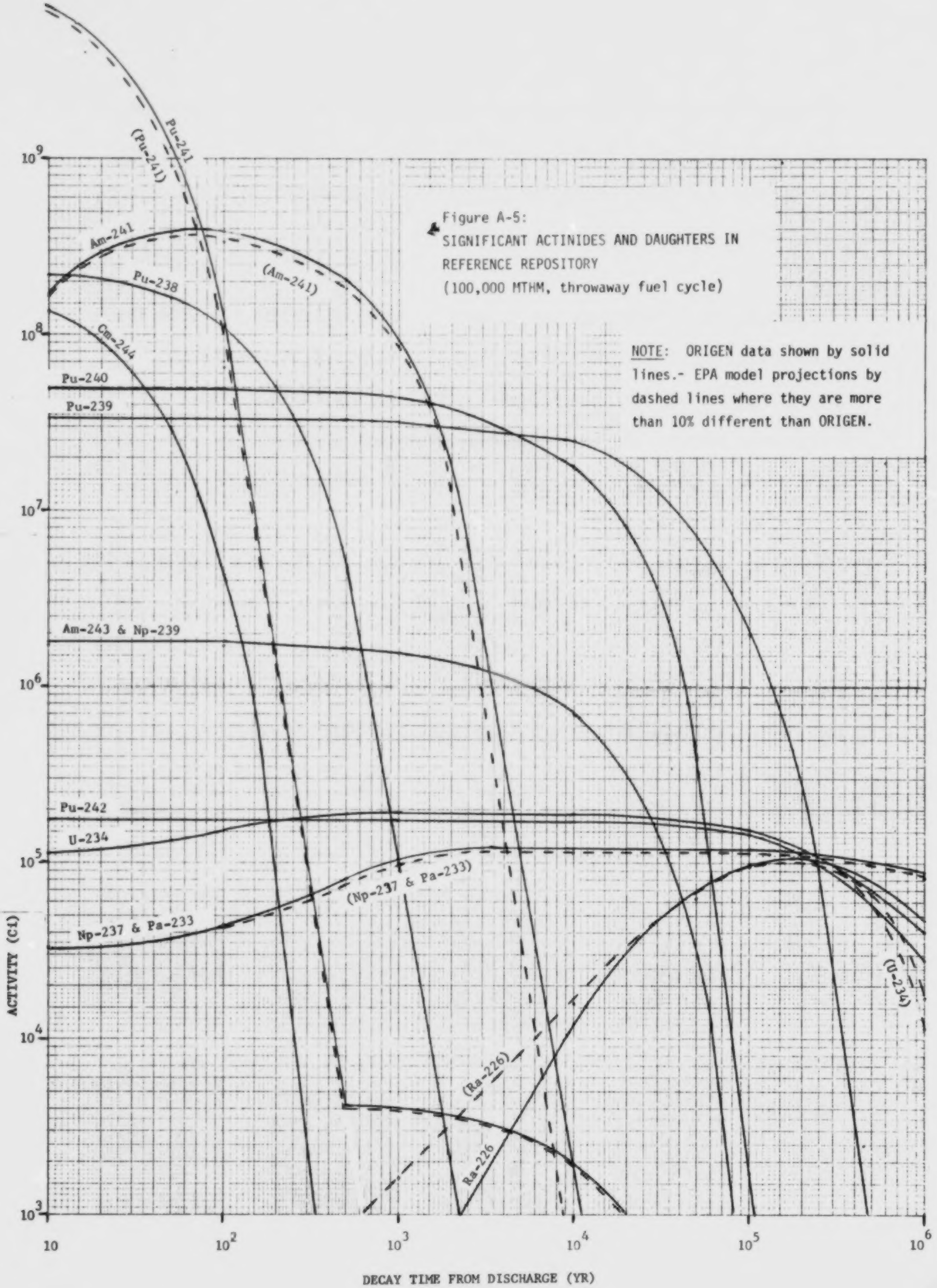

Figure A-5:
SIGNIFICANT ACTINIDES AND DAUGHTERS IN REFERENCE REPOSITORY
(100,000 MTHM, throwaway fuel cycle)

NOTE: ORIGEN data shown by solid lines.- EPA model projections by dashed lines where they are more than 10% different than ORIGEN.

The transport of radionuclides through the aquifer to the environment is another matter. Releases through this pathway can occur over very long time periods. The buildup of Ra-226 in our reference aquifer can become significant. If the releases are integrated only through a 10,000 year time period, the transit time of Ra-226 in our reference aquifer is too long for it to be released in significant amounts to the environment. However, if the integration of releases is extended to hundreds of thousands of years, it would be prudent to specifically analyze the potential releases of Ra-226 via the aquifer pathway.

Appendix B

RADIONUCLIDE TRANSPORT IN GROUNDWATER

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The analytical solution of a radionuclide transport equation in a groundwater stream can be greatly simplified if the diffusion effect is neglected (BH 80); however, this may introduce some modeling error. This Appendix evaluates the modeling error introduced by this simplification.

For the purpose of this discussion, we assume the effect of radionuclide retardation in the host formation is negligible. Therefore, the basic equations may be written as

$$\frac{\partial \dot{Q}}{\partial t} - \frac{D}{R_d} \frac{\partial^2 \dot{Q}}{\partial X^2} + \frac{v}{R_d} \frac{\partial \dot{Q}}{\partial X} + \lambda \dot{Q} = 0 \qquad \text{(B-1)}$$

The boundary condition with a source term representing a drilling event which hits a canister may be written by assuming that the contents of the canister are released directly into the aquifer with little or no resistance from the host rock or drilling borehole. That is:

$$\dot{Q} = fLQ_o e^{-\lambda t_e} e^{-(L+\lambda)(t-t_e)} U(t - t_e) \qquad \text{(B-2)}$$

In these equations:

$\dot{Q}$ = the rate of radionuclide passing through a section.

D = the coefficient of hydrodynamic dispersion

R_d = the retardation factor of the overlying aquifer

v = the groundwater velocity

λ = the decay constant

L = the release rate constant

Q_o = the initial inventory of radionuclide

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X = the space coordinate

t = the time of interest

t_e = the event time.

f = the fraction of repository affected

The analytical solution for equation B-1--neglecting the dispersion term and using equation B-2 as the boundary condition--is:

$$\dot{Q} = fL\dot{Q}_o e^{-\lambda t_e} e^{-L(t-t_e-R_dX/v)} U(t-t_e-R_dX/v) \tag{B-3}$$

The analytical solution without neglecting the dispersion term, on the other hand, is (ADL 79d):

$$\dot{Q} = \frac{fL\dot{Q}_o}{2} e^{-L(t - t_e)} e^{(vX/2D-\lambda t-GX)} \operatorname{erfc}[X/2 \overline{R_d/D(t-t_e)} - \overline{G D(t-t_e)/R_d}] \tag{B-4}$$

where G is:

$$G = \overline{\frac{v^2}{4D} \quad \frac{R_dL}{D}} \tag{B-5}$$

We have calculated health effects using the environmental dose commitment of the total quantity of radionuclides released to the biosphere over a specified time period. Although integration of equation B-4 with respect to time cannot be obtained analytically, we can integrate equation B-3. Therefore, the modeling process can be simplified by neglecting the dispersion term. In order to evaluate the error introduced by omitting the dispersion effect, we investigated four radionuclides that are expected to contribute the major portion of health effects from groundwater transport pathways. They are technetium-99, neptunium-237, strontium-90 and plutonium-239. We analyzed the relative error of neglecting the dispersion effect for the postulated hydrogeological conditions employed in this analysis. The results presented in Table B-1 indicate the relative errors are generally low for all radionuclides except plutonium-239. Although there is a significant difference in the case of plutonium-239, the net release of radioactivity is expected to be small enough to be negligible.

We therefore conclude that we can neglect the dispersion effect under the assumed hydrogeological conditions without introducng significant error in our assessments of health effects.

Table B-1

Relative Error Due to Omission of Diffusion Effect

Radio-nuclide	Retardation Factor	Decay Number	Total Activity Released Downstream (Ci/Ci)[1]		Error (percent)
			With Diffusion	Without Diffusion	
Tc-99	1.0	0.00176	$9.9829\text{x}10^{-1}$	$9.9824\text{x}10^{-1}$	0.005
Np-237	100	0.00017	$9.8315\text{x}10^{-1}$	$9.8314\text{x}10^{-1}$	0.0013
Sr-90	100	12.2	0.0000	0.0000	0.0000
Pu-239	10000	0.0151	$1.5506\text{x}10^{-64}$	$2.6396\text{x}10^{-66}$	-----

[1] Note: Total activity in curies released at downstream end due to impulse release of activity at upstream end.

Appendix C

DERIVATIONS OF EQUATIONS

C.1 Solution to Equation 5-3a

$$V \frac{dC(t)}{dt} = LfQ_c(t) - \lambda VC(t) \qquad (5\text{-}3a)$$

where: $$Q_c(t) = Q_o e^{-\lambda t} e^{-L(t - t_c)} \qquad (5\text{-}3b)$$

Equation 5-3a is a differential equation of the form:

$$p(s)y + y' = q(s)$$

that can be rewritten as:

$$\lambda C(t) + dC(t)/dt = \frac{Lf}{V} Q_c(t)$$

with: $$p(t) = \lambda$$

$$q(t) = \frac{Lf}{V} Q_c(t) = \frac{Lf}{V} [Q_o e^{-\lambda t} e^{-L(t - t_c)}]$$

An integrating factor, $\mu(t)$, is:

$$e^{\int^t p(s)ds} = e^{\int^t \lambda ds} = e^{\lambda t}$$

Multiplying equation 5-3a by the integrating factor:

$$e^{\lambda t} [\lambda C(t) + dC(t)/dt] = [\frac{Lf}{V} Q_o e^{-\lambda t} e^{-L(t-t_c)}] e^{\lambda t}$$

and integrating yields:

$$\int_{t_c}^{t_i} \frac{dC(t)e^{\lambda t}}{d(t)} dt = \frac{Lf}{V} \int_{t_c}^{t_i} Q_o e^{-L(t-t_c)} dt$$

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Evaluating this equation gives:

$$C(t_i)e^{\lambda t_i} - C(t_c)e^{\lambda t_c} = \frac{Lf}{V}\left(\frac{-1}{L}\right) Q_0 \left[e^{-L(t_i-t_c)} - e^{-L(0)}\right]$$

But the concentration at the time of canister failure, $C(t_c)$, is zero, therefore:

$$C(t_i)\, e^{\lambda t_i} = -\frac{fQ_0}{V} e^{-L(t_i - t_c)} + \frac{fQ_0}{V}$$

which simplifies to:

$$C(t_i) = \frac{fQ_0}{V} e^{-\lambda t_i} \left[1 - e^{-L(t_i - t_c)}\right] \qquad (5\text{-}4)$$

giving the concentration at any time, t_i.

C.2 Solution to Equation 5-5:

$$VdC(t)/dt = LfQ_c(t) - \lambda VC(t) - V(t)^{*}C(t) \qquad (5\text{-}5)$$

where: $$Q_c(t) = Q_0 e^{-\lambda t}\, e^{-L(t-t_c)} \qquad (5\text{-}3b)$$

Equation 5-5 is a differential equation of the form:

$$p(s)y + y' = q(s)$$

which can be seen by rewriting equation 5-5 in the form:

$$[\lambda + (V^{*}(t)/V)]\; C(t) + dC(t)/dt = \frac{Lf}{V} Q_c(t)$$

and setting: $$p(t) = \lambda + V^{*}(t) / V$$

$$q(t) = \frac{Lf}{V} Q_c(t) = \frac{Lf}{V} \left[Q_0 e^{-\lambda t}\, e^{-L(t - t_c)}\right]$$

An integrating factor, $\mu(t)$, is given by:

$$\mu(t) = e^{\int^{t} p(s)ds} = e^{\int^{t} [\lambda + V^{*}(s)/V]\, ds}$$

the solution is of the form:

$$C(t) = \frac{1}{\mu(t)} \int_{t_e}^{t} \mu(s)q(s)ds + \frac{C(te)\mu(te)}{\mu(t)}$$

where: t_e = time release was initiated (the event time)

$C(t_e)$ = the concentration of the radionuclide immediately before the event time (equation 5-4).

C.3 Solution to Equation 5-7

$$V \frac{dC(t)}{dt} = LfQ_c(t) - \lambda VC(t) - V_{aq}C(t) \qquad (5\text{-}7)$$

Equation 5-7 is a differential equation of the form:

$$p(s)y + y' = q(s)$$

which can be seen by rewriting equation 5-7 in the form:

$$[\lambda + V_{aq}/V]\ C(t) + \frac{dC(t)}{dt} = \frac{Lf}{V} Q_c(t)$$

and setting $p(t) = \lambda + V_{aq}/V$

$$q(t) = \frac{Lf}{V} Q_c(t) = \frac{Lf}{V} Q_o e^{-\lambda t} e^{-L(t-t_c)}$$

An integrating factor is given by:

$$\mu(t) = e^{\int^{t} p(s)\, ds} = e^{\int^{t} [\lambda + V_{aq}/V]\, ds} = e^{\lambda t} e^{tV_{aq}/V}$$

The solution is of the form:

$$C(t_i) = \frac{1}{\mu(t_i)} \int_{t_e}^{t_i} \mu(s)q(s)ds + \frac{C(t_e)\mu(t_e)}{\mu(t_i)}$$

$$C(t_i) = \left\{ \begin{array}{l} \dfrac{LfQ_o}{V_{aq}-LV} \left[e^{-(\lambda+V_{aq}/V)t_i}\, e^{Lt_c}\, [e^{(V_{aq}/V-L)t_i} - e^{(V_{aq}/V-L)t_e}] \right] \\ + \dfrac{C(t_e)\mu(t_e)}{\mu(t_i)} \end{array} \right\}$$

where: t_i = the time of interest

t_e = time of event (assuming $t_i \geq t_e \geq t_c$)

$C(t_e) = \frac{fQ_o}{V} e^{-\lambda t_e} [1 - e^{-L(t_e - t_c)}]$ (from Equation 5-4)

C.4 Solution to Equation 5-18

$$\frac{dC(t)}{dt} = LQ_c(t)/V(t) - \lambda C(t)$$

can be written in the form:

$$p(s)y + y' = q(s)$$

as:

$$\lambda C(t) + \frac{dC(t)}{dt} = \frac{LQ_c(t)}{V(t)}$$

with:

$$p(s) = \lambda$$

$$q(t) = L\,Q_c(t) \,/\, V(t)$$

$$\mu(t) = e^{\int^t p(s)ds} = e^{\lambda t}$$

The solution is of the form:

$$C(t) = \frac{1}{\mu(t)} \int_{T_{rch}}^{t} \mu(s)q(s)ds + \frac{C(T_{rch})\mu(T_{rch})}{\mu(t)}$$

where:

T_{rch} = saturation time

$$C(t) = e^{-\lambda t} \int_{T_{rch}}^{t} [e^{\lambda s} LQ_c(s)/V(s)]ds + \frac{C(T_{rch})e^{\lambda T_{rch}}}{e^{\lambda t}}$$

This equation must be solved numerically.

C.5 Solution to Equation 5-5 with V*(t) from equation 5-20

$$VdC(t)/dt = LfQ_c(t) - \lambda VC(t) - V^*(t)C(t) \qquad (5\text{-}5)$$

$$V^*(t) = KAi(t)c(\mu) = K\,A\,(ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a) \qquad (5\text{-}20)$$

From Section C.2, equation 5.5 is of the form:

$$p(s)y + y' = q(s)$$

with:

$$q(t) = \frac{Lf}{V}[Q_o\, e^{-\lambda t}\, e^{-L(t - t_c)}]$$

$$p(t) = \lambda + V^*(t)/V = \lambda + K\,A\,i(t)\,c(\mu)\,/\,V$$

$$= \lambda + K\,A\,(ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a)\,/\,V$$

$$\mu(t) = e^{\int^t p(s)ds}$$

The solution is of the form:

$$C(t_i) = \frac{1}{\mu(t_i)}\int_{t_c}^{t_i} \mu(s)q(s)ds + \frac{C(t_c)\mu(t_c)}{\mu(t_i)}$$

and, in this case, $C(t_c) = 0$, so the last term vanishes.

C.6 Solution to Equation 5-28

$$V \frac{dC(t)}{dt} = LfQ\, e^{-\lambda t}\, e^{-L(t-t_c)} - \lambda VC(t) - Ki(t)c(\mu)AC(t) \qquad (5\text{-}28)$$

is of the form:

$$p(s)y + y' = q(s)$$

with: $p(t) = \lambda + V^{*}(t) \;/\; V = \lambda + K\; i(t)\; c(\mu)\; A \;/\; V$

$$q(t) = LfQ_0\, e^{-\lambda t}\, e^{-L(t-t_c)}$$

$$\mu(t) = e^{\int^{t} p(s)ds} = e^{\lambda t}\, e^{\int^{t} V^{*}(s)/V\, ds}$$

$$= e^{\lambda t}\, e^{\int^{t} [Ki(s)c(\mu)A/V]\, ds}$$

and: $i(t)c(\mu) = ae^{-\alpha t} + be^{-\beta t} + i_a ce^{-\gamma t} + i_a$

so: $\mu(t) = e^{\lambda t}\, e^{\int^{t} [K(ae^{-\alpha s} + be^{-\beta s} + i_a ce^{-\gamma s} + i_a)A/V]\, ds}$

The solution is of the form:

$$C(t) = \frac{1}{\mu(t)} \int_{t_e}^{t} \mu(s)q(s)ds + \frac{C(t_e)\mu(t_e)}{\mu(t)}$$

and, since the brine pocket is empty initially:

$$C(t_e) = 0$$

The total quantity of radionuclide released is

$$Q = \int_{t_e}^{t} C(s)V^{*}(s)\,ds$$

where $C(t)$ is either the solution to Equation 5-28 or, for a solubility limited radionuclide, C_0, the solubility limit. The volumetric flow, $V^{*}(t)$, is either:

$$V^{*}(t) = K(t)i(t)c(\mu)A$$

or, for a volumetric flow limited by the aquifer:

V_{aq} = the flow limit of the aquifer.

Appendix D

MORE CONSERVATIVE PROBABILITY ESTIMATES

In their report Arthur D. Little, Inc. (ADL) provides more conservative assumptions concerning various events affecting a repository, which they have labeled "second" estimates (ADL 79d). We have not utilized all of their second estimates, but we have examined the effects of the higher probabilities of various events. The bases for these second estimates are discussed below. The calculated values of the second estimate probabilities are presented in Table D-1, where they are compared with ADL's "first" estimates.

D.1 Human Intrusion, Drilling

The second estimate probabilities of drilling into a bedded salt, domed salt, shale or basalt repository are based on the reference probability of drilling into a bedded salt repository. ADL's first estimate for a bedded salt repository is based on exploratory drilling for oil and minerals. The more conservative values also include occasional drilling for water. ADL's second estimate for granite is based on drilling for water, geothermal, and mineral exploration and possible development of geothermal wells.

D.2 Faulting

The second estimate faulting probabilities are based on different geologic eras in selected locations. The technique for calculating the probabilities is presented in Chapter 5. Calculations differ for each repository, thus they will be discussed briefly according to repository type. ADL chose f equal to 5 as the number of faults expected per repository.

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Table D-1

More Conservative ("Second Estimate") Frequencies of Occurrence for Various Events

(Events per year) (ADL 79d)

Event		Bedded Salt	Domed Salt	Granite	Basalt	Shale
Drilling *	2nd estimate	$5x10^{-2}$	$5x10^{-2}$	$2x10^{-2}$	$5x10^{-2}$	$5x10^{-2}$
	1st estimate	$2x10^{-2}$	$2x10^{-3}$	$1x10^{-2}$	$1x10^{-2}$	$2x10^{-2}$
Faulting	2nd estimate	$4x10^{-7}$	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-5}$	$4x10^{-7}$
	1st estimate	$2x10^{-8}$	$3x10^{-7}$	$2x10^{-8}$	$5x10^{-7}$	$2x10^{-8}$
Breccia Pipe +	2nd estimate	$1x10^{-6}$	--	--	--	--
	1st estimate	$1x10^{-8}$	--	--	--	--
Volcano	2nd estimate	$1x10^{-8}$	$1x10^{-10}$	$1x10^{-8}$	$1x10^{-8}$	$1x10^{-8}$
	1st estimate	$1x10^{-10}$	$1x10^{-10}$	$1x10^{-10}$	$6x10^{-10}$	$1x10^{-10}$
Meteorite		For all media, both 1st and 2nd estimates are: $4x10^{-11}$				

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* Occurrence rate is assumed to be zero during the first 100 years after disposal, and somewhat higher than the rates shown during the second 100 years after disposal.

+ Occurrence rate is assumed to be zero during first 500 years after disposal.

D.2.1 Bedded Salt

The second estimate for faulting in bedded salt is based on mid-Tertiary faulting in the Paradox Basin with N = 25 million years.

D.2.2 Domed Salt

The second estimate for faulting in domed salt is based on Gulf Coast faulting, with the latest faulting occurring during the Quaternary period and a minimum age of one million years.

D.2.3 Shale

The second estimate for faulting in shale is based on the same assumptions as for bedded salt.

D.2.4 Granite

The second estimate for faulting in granite is based on an active site in the basin and range province in the Southwestern United States. The age would be at least one million years.

D.2.5 Basalt

The second estimate for basalt is based on a site where the most recent faulting is more recent than the Quaternary age of one million years.

D.3 Breccia Pipe

The ADL second estimate for breccia pipes is discussed in Section 5.2.4 of Chapter 5--a value of 1 x 10^{-6} events per year.

D.4 Volcanoes

For the second estimates, ADL assumed that repository sites are located near areas that have experienced volcanic activity over the past ten million years. A number of volcanic fields were considered, such as the Flagstaff, Arizona, area where 85 vents are estimated to exist in an area 6400 km^2 (ADL 79d). The time over which these developed is thought to be at least 10^7 years. It is important to note the value calculated for the second estimate should not be applied to the specific volcano fields from whose parameters they have been calculated. They represent only averages, and detailed site investigation could introduce other factors that might significantly alter the estimate for an individual site. We believe thay are reasonable for generic calculations.

Many other calculations yielded similar values, and so we selected a frequency of 1×10^{-8} events per year for second estimates for all media except salt domes. In the case of salt domes, the second estimate is the same as the reference case estimate.

D.5 Meteorites

Since the calculated probability for meteorites is a statistically derived estimate and independent of location, the second estimate has the same value as the reference estimate.

Appendix E

FORTRAN LISTING OF COMPUTER PROGRAM

(REPRISK)

```
C***** CC: 000 ***********************************************************
C                                                      MARCH 13, 1981    *
C     REPRISK                                                            *
C             -- MODIFIED TO TREAT EERF ENVIRONMENTAL PATHWAY MODELS     *
C                (PATHWAY INPUT FILES OF FT03 AND 04 ARE LABELED)        *
C             -- MODIFIED TO INCLUDE NEW A.D.LITTLE RELEASE MODELS       *
C             -- MODIFIED TO TREAT MULTIPLE DRILLING EVENTS              *
C     FOR INPUT INSTRUCTIONS SEE REPRISK INPUT GUIDE DATED JAN 21, 1981 *
C                                                                        *
C                                                                        *
C***** CC: 000 ***********************************************************
C
      COMMON /BLOCK1/ E1,TAX,V,AREA(10),K1(10),RNLDX(20),NC,ND,Y1X,IEX
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      DIMENSION F(6),A(4),HELAB(6),RT(16),PROBT(8),CNT(8)
C
      DIMENSION TITLE(120),DASH(33),FMTA(10),FMTB(11),FMTC(10),HFA(5),
     1      HFB(8,5),HFC(5),STARS(29),EVENT(4),HFSTIT(19),HFGTIT(19),
     2      SOMLAB(6),GENLAB(6),RROLAB(6),CURLAB(6)
C
      DIMENSION AMEAN1(12,10)
      DIMENSION     TEDC (12),                NOUT ( 7)
C------------------ NDCTM ** --------------- NOUT8 **
C
      DIMENSION
     1  EVNT  (10),   PROB (10,          25),   RNID (20),   RNLD1 (20),
     2  NEVTT (10),   CNS  (10,          25),   NRNTY(20),   RNQ01 (20),
     3  FHIT  (10),   CNG  (10,          25),   RNLD (20),   RNKD  (20),
     4  FTANK (10),   CNR  (10,          25),   RNQO (20),   RNSOL (20),
     5  VTANK (10),   NRSMX(10,          25),   RNDS (20),   RNQOX (20),
     6  EDES  (10,4), NRGMX(10,          25),   RNDA (20),
     7  PORS  (10),   NRRMX(10,          25),   RNDS1(20),   LR    (20),
     8                    X(10,          25),   RNDS2(20),   RLMT(3,20),
     9                    Y(10,          25),   LAMS (20),   RRISKS(20),
     A  KPRIM (10),   FRATE(10,          25),                RRISKG(20),
     B                NDEVS(10,          25),                RRISKR(20),
     C  NDCASE(10),   RISKS(10),  TEVNT(25),
     D  VDRILL(10),   RISKG(10),  NENTT(25),
     E                RISKR(10),  TOBND(25),
     F                CNSR (10,          25,          20),
     G                CNGR (10,          25,          20),
     H                CNRR (10,          25,          20),
     I        CSR(200,20),CGR(200,20),CRR(200,20)
C------- NEVSM ** --- NEVSM ** -- NEVTM ** ---- NRNM  ** --- NRNM **
C
```

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```
      DIMENSION    HFS1 (20),     HFS7 (20),     HFG1 (20),     HFG7 (20).
     1             HFS2 (20),     HFS8 (20),     HFG2 (20),     HFG8 (20),
     2             HFS3 (20),     HFS9 (20),     HFG3 (20),     HFG9 (20),
     3             HFS4 (20),     HFS10(20),     HFG4 (20),     HFG10(20),
     4             HFS5 (20),     HFS11(20),     HFG5 (20),     HFG11(20),
     5             HFS6 (20),     HFS12(20),     HFG6 (20),     HFG12(20)
C------------------ NRNM ** ----- NRNM ** ----- NRNM ** ----- NRNM **
C
      REAL*8 DDASH/8H--------/
      REAL*8 CNS,CNG,CNR,PROB,PROBT,CNT,X,Y,RISKS,RISKG,RISKR,TRISKS,
     1       TRISKG,TRISKR
      REAL*4 LAMS,LAMR,LAMG,LAMW,MESS1N,MESSA,MESS1A,MESSAA,LR,K1,KPRIM
C
      DATA TITLE/120*4H    /, DASH/33*4H----/, STARS/29*4H****/,
     1     BLANKS/4H    /
      DATA SOMLAB/4H SOM,4HATIC,4H HEA,4HLTH ,4HEFFE,4HCTS /
      DATA GENLAB/4H GEN,4HETIC,4H HEA,4HLTH ,4HEFFE,4HCTS /
      DATA RROLAB/4H    ,4H REL,4HEASE,4H RAT,4HIOS ,4H    /
      DATA CURLAB/4H    ,4H CUR,4HIES ,4HRELE,4HASED,4H    /
      DATA EVENT/4H    ,4H EVE,4HNT  ,4H    /
      DATA FMTA/4H(   ,4H1H ,,4H17X,,4H8( 2,4HX,  ,4H I6,,4H' YE,4HARS',
     1          4H  )/,4H1H )/
      DATA FMTB/4H(   ,4H1H ,,4H4A4,,4H'*',,4H7( 5,4HX,1P,4HE9.2,4H  ),,
     1          4H1( 5,4HX,A9,4H  ))/
      DATA FMTC/4H(   ,4H1H ,,4H 4X,,4HF5.1,4H,7X,,4H'*',,4H8( 6,4HX,  ,
     1          4H2A4 ,4H  ))/
      DATA HFA /4H4(16,4H5(11,4H6( 7,4H7( 4,4H8( 2/
      DATA HFB /4H1(19,4H2(19,4H3(19,4H4(19,4*4H    ,
     1          4H1(14,4H2(14,4H3(14,4H4(14,4H5(14,3*4H    ,
     2          4H1(10,4H2(10,4H3(10,4H4(10,4H5(10,4H6(10,2*4H    ,
     3          4H1( 7,4H2( 7,4H3( 7,4H4( 7,4H5( 7,4H6( 7,4H7( 7,4H    ,
     4          4H1( 5,4H2( 5,4H3( 5,4H4( 5,4H5( 5,4H6( 5,4H7( 5,4H8( 5/
      DATA HFC /4H4(20,4H5(15,4H6(11,4H7( 8,4H8( 6/
      DATA AFORMA,AFORMB/4H  ),,4HX,A9/
C
      DATA TEDC   /12*0.0/
      DATA EVNT   /10*0.0/
      DATA TEVNT  /25*0.0/
      DATA TOBND  /25*0.0/
      DATA RNID   /20*0.0/
C
      DO 1246 I = 1,10
      CVA(I) = 0.
      ALPH(I) = 1.
 1246 CONTINUE
C
```

```
      CALL ERRSET(208,0,-1,1)
      NDCTM = 12
      NEVTM = 25
      NOUT8 = (NEVTM/8) + 1
      NEVSM = 10
      NRNM  = 20
C
      NDCT  =  0
      NEVT  =  0
      NEVS  =  0
      NRN   =  0
C
      IX    =  0
      IPATH =  0
      IRLMT =  1
      NINT  =  0
C
      TDINT = 0.0
      CVC   = 0.0
      NCOF  = 10
C
C
      DO 1234 I=1,NEVTM
      DO 1234 J=1,NEVSM
      FRATE(J,I) = 0.0
 1234 PROB(J,I)  = 0.0
C
      DO 1244 I=1,NRNM
      RNLD1(I) = 0.0
      RNQO1(I) = 0.0
      RNLDX(I) = 0.0
 1244 RNQOX(I) = 0.0
C
  555 NDOT  =  0
C
      READ (5,13,ERR=999) NLINE,IREP,NSG,NINT,NMAT,NPCA,NPCP,NDOO,NN,NT,
     1                    IDRILL
      WRITE (6,72)
      IF (NINT .LE. 1)
     1 WRITE (6,16) NLINE,IREP,NSG,NINT,NMAT,NPCA,NPCP,NDOO,NN,NT,IDRILL
   16 FORMAT (1H ,10X,16I5)
   13 FORMAT (16I5)
      IF (NSG  .EQ. 0) NSG  = 3
      IF (NINT .EQ. 0) NINT = 2
      IF (NMAT .EQ. 0) NMAT = 2
      IF (NPCA .EQ. 0) NPCA = 2
      IF (NPCP .EQ. 0) NPCP = 1
      IF (NDOO .EQ. 0) NDOO = 3
      IF (IDRILL .EQ. 0) IDRILL = 1
```

```
    GO TO (251,252,253,254,255,256,257), NSG
251 NPA  = 1
    NPB  = 1
    NPC  = 1
    NTS  = 1
    NTG  = 0
    NTR  = 0
    GO TO 258
252 NPA  = 2
    NPB  = 2
    NPC  = 1
    NTS  = 0
    NTG  = 1
    NTR  = 0
    GO TO 258
253 NPA  = 3
    NPB  = 3
    NPC  = 1
    NTS  = 0
    NTG  = 0
    NTR  = 1
    GO TO 258
254 NPA  = 1
    NPB  = 2
    NPC  = 1
    NTS  = 1
    NTG  = 1
    NTR  = 0
    GO TO 258
255 NPA  = 1
    NPB  = 3
    NPC  = 2
    NTS  = 1
    NTG  = 0
    NTR  = 1
    GO TO 258
256 NPA  = 2
    NPB  = 3
    NPC  = 1
    NTS  = 0
    NTG  = 1
    NTR  = 1
    GO TO 258
257 NPA  = 1
    NPB  = 3
    NPC  = 1
    NTS  = 1
    NTG  = 1
    NTR  = 1
258 IF (NDOO .EQ. 2) NDOT = 1
```

```
      N2 = NLINE + 1
      GO TO (100,102,103,104,105,106,107), N2
      CALL ERROR (1,N1,N2,F,A,IX)
  102 READ  (5,11) (TITLE(I),I=1,20)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,20)
   11 FORMAT (20A4)
   12 FORMAT (18X,20A4)
      GO TO 108
  103 READ  (5,11) (TITLE(I),I=1,40)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,40)
      GO TO 108
  104 READ  (5,11) (TITLE(I),I=1,60)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,60)
      GO TO 108
  105 READ  (5,11) (TITLE(I),I=1,80)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,80)
      GO TO 108
  106 READ  (5,11) (TITLE(I),I=1,100)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,100)
      GO TO 108
  107 READ  (5,11) (TITLE(I),I=1,120)
      IF (NINT .LE. 1) WRITE (6,12) (TITLE(I),I=1,120)
  108 CONTINUE
C
C***** CC: 000 *********************************************************
C                                                                      *
C                       REPRISK INPUT                                  *
C                                                                      *
C              REFER TO INPUT GUIDE FOR ASSISTANCE                     *
C                                                                      *
C***** CC: 000 *********************************************************
  100 READ (5,10,ERR=999,END=190) N1,N2,(F(I),I=1,6),(A(I),I=1,4)
      IF (NINT .LE. 1) WRITE (6,25) N1,N2,(F(I),I=1,6),(A(I),I=1,4)
   25 FORMAT(1H ,10X,I2,2X,I2,6(2X,1PE10.2),2X,4A4)
   10 FORMAT (2I2,6E10.4,4A4)
C
C***** CC: 000 *******************************************************
C                                                                    *
C***** TYPE 10 CARD ENTERS DOSE INTEGRATION TIME                     *
C                                                                    *
C **   IF SET EQUAL TO ZERO, DOSE INTEGRATION IS TAKEN TO BE THE     *
C **   TIME PERIOD OVER WHICH EVENTS ARE CONSIDERED (THE DOSE        *
C **   COMMITMENT TIME)                                              *
C                                                                    *
C***** CC: 000 *******************************************************
      IF (N1 .NE. 10) GO TO 200
C
      TDINT = F(1)
      GO TO 100
C
```

```
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 11 CARDS ENTER DOSE COMMITMENT TIMES                       *
C                                                                      *
C***** CC: 000 *********************************************************
  200 IF (N1 .NE. 11) GO TO 300
C
      DO 1001 I=1,6
      IF (F(I) .EQ. 0.0) GO TO 1001
      DO 1002 J=1,NDCTM
      IF (TEDC(J) .NE. 0.0) GO TO 201
      TEDC(J) = F(I)
      NDCT = J
      GO TO 1001
  201 IF (F(I) .EQ. TEDC(J)) GO TO 1001
      IF (F(I) .GT. TEDC(J)) GO TO 1002
      SAVEA = TEDC(J)
      TEDC(J) = F(I)
      JJ = J + 1
      DO 1003 K=JJ,NDCTM
      IF (TEDC(K) .NE. 0.0) GO TO 202
      TEDC(K) = SAVEA
      NDCT = K
      GO TO 1001
  202 SAVEB = TEDC(K)
      TEDC(K) = SAVEA
 1003 SAVEA = SAVEB
 1002 CONTINUE
 1001 CONTINUE
      GO TO 100
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 20 CARDS ENTER EVENT TIMES                                 *
C                                                                      *
C***** CC: 000 *********************************************************
  300 IF (N1 .NE. 20) GO TO 400
C
      DO 2001 I=1,6
      IF (F(I) .EQ. 0.0) GO TO 2001
      DO 2002 J=1,NEVTM
      IF (TOBND(J) .NE. 0.0) GO TO 301
      TOBND(J) = F(I)
      NEVT = J
      GO TO 2001
  301 IF (F(I) .EQ. TOBND(J)) GO TO 2001
      IF (F(I) .GT. TOBND(J)) GO TO 2002
      SAVEA = TOBND(J)
      TOBND(J) = F(I)
      JJ = J + 1
      DO 2003 K=JJ,NEVTM
      IF (TOBND(K) .NE. 0.0) GO TO 302
      TOBND(K) = SAVEA
      NEVT = K
      GO TO 2001
  302 SAVEB = TOBND(K)
      TOBND(K) = SAVEA
 2003 SAVEA = SAVEB
 2002 CONTINUE
 2001 CONTINUE
      GO TO 100
C                                                                      *
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 22 CARD ENTERS ASSUMPTIONS ON DISTRIBUTION OF MATERIAL     *
C***** RELEASED TO THE ATMOSPHERE                                      *
C                                                                      *
C***** CC: 000 *********************************************************
  400 IF (N1 .NE. 22) GO TO 450
C
      FAL = F(1)
      FLL = F(2)
      FAW = F(3)
      GO TO 100
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 23 AND 24 CARDS ENTER CHARACTERIZATIONS OF EVENT EFFECTS *
C***** ON THE REPOSITORY                                               *
C                                                                      *
C***** CC: 000 *********************************************************
  450 IF (N1 .NE. 23) GO TO 451
C
      DO 3001 I=1,NEVSM
      IF (EVNT(I) .EQ. 0.0) GO TO 402
      IF (EVNT(I) .NE. F(1)) GO TO 3001
      NEVTT(I) = N2
      FHIT(I)  = F(2)
      FTANK(I) = F(3)
      VTANK(I) = F(4)
      VDRILL(I) = F(5)
      DO 3002 J=1,4
 3002 EDES(I,J) = A(J)
      GO TO 100
 3001 CONTINUE
```

```
  402 NEVS = NEVS + 1
      EVNT(NEVS)   = F(1)
      NEVTT(NEVS) = N2
      FHIT(NEVS)   = F(2)
      FTANK(NEVS) = F(3)
      VTANK(NEVS) = F(4)
      VDRILL(NEVS) = F(5)
      DO 3003 J=1,4
 3003 EDES(NEVS,J) = A(J)
      GO TO 100
C
  451 IF (N1 .NE. 24) GO TO 460
C
      DO 3101 I=1,NEVSM
      IF (EVNT(I) .EQ. 0.0) GO TO 999
      IF (EVNT(I) .NE. F(1)) GO TO 3101
      K1(I)      = F(2)
      KPRIM(I)   = F(3)
      PORS(I)    = F(4)
      AREA(I)    = F(5)
      GO TO 100
 3101 CONTINUE
      GO TO 999
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 25 CARDS ENTER EVENT FAILURE RATE DATA                     *
C                                                                      *
C **   THE AVERAGE FAILURE RATE OF EACH EVENT TYPE OCCURRING WITHIN    *
C **   EACH EVENT TIME PERIOD MUST BE ENTERED ON TYPE 24 CARDS.        *
C **   FAILURE RATES MUST BE ASSOCIATED WITH INCREASING EVENT TIME     *
C **   PERIODS REGARDLESS OF THE ORDER ON THE TYPE 20 CARDS            *
C                                                                      *
C***** CC: 000 *********************************************************
  460 IF (N1 .NE. 25) GO TO 470
C
      DO 3004 I=1,NEVSM
      IF (EVNT(I) .EQ. 0.0) GO TO 999
      IF (EVNT(I) .NE. F(1)) GO TO 3004
      GO TO (403,404,405,406,407,408), N2
      CALL ERROR (3,N1,N2,F,A,IX)
  403 DO 3005 J=2,6
 3005 FRATE(I,J-1)  = F(J)
      GO TO 100
  404 DO 3006 J=2,6
 3006 FRATE(I,J+4)  = F(J)
      GO TO 100
  405 DO 3007 J=2,6
 3007 FRATE(I,J+9)  = F(J)
      GO TO 100
  406 DO 3008 J=2,6
 3008 FRATE(I,J+14) = F(J)
      GO TO 100
  407 DO 3009 J=2,6
 3009 FRATE(I,J+19) = F(J)
      GO TO 100
  408 DO 3010 J=2,6
 3010 FRATE(I,J+24) = F(J)
      GO TO 100
 3004 CONTINUE
      GO TO 999
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 26 CARDS ENTER EVENT INITIAL PROBABILITY (INSTEAD OF       *
C***** FAILURE RATE DATA)                                              *
C                                                                      *
C***** CC: 000 *********************************************************
  470 IF (N1 .NE. 26) GO TO 500
C
      DO 3011 I=1,NEVSM
      IF (EVNT(I) .EQ. 0.0) GO TO 999
      IF (EVNT(I) .NE. F(1)) GO TO 3011
      PROB(I,1) = F(2)
      GO TO 100
 3011 CONTINUE
      GO TO 999
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 30, 31, AND 32 CARDS ENTER RADIONUCLIDE DATA               *
C                                                                      *
C***** CC: 000 *********************************************************
  500 IF (N1 .NE. 30) GO TO 501
C
      DO 4001 I=1,NRNM
      IF (RNID(I) .EQ. 0.0) GO TO 502
      IF (RNID(I) .NE. F(1)) GO TO 4001
      NRNTY(I) = N2
      RNLD(I)  = 0.693/F(2)
      RNQO(I)  = F(3)
      LR(I)    = F(4)
      RNDA(I)  = F(5)
      RNSOL(I) = F(6)
      RNDS1(I) = A(1)
      RNDS2(I) = A(2)
      GO TO 100
 4001 CONTINUE
```

```
  502 NRN = NRN + 1
      RNID(NRN)  = F(1)
      NRNTY(NRN) = N2
      RNLD(NRN)  = 0.693/F(2)
      RNQO(NRN)  = F(3)
      LR(NRN)    = F(4)
      RNDA(NRN)  = F(5)
      RNSOL(NRN) = F(6)
      RNDS1(NRN) = A(1)
      RNDS2(NRN) = A(2)
      GO TO 100
C
  501 IF (N1 .NE. 31) GO TO 503
      DO 4002 I=1,NRNM
      IF (RNID(I) .EQ. 0.0) GO TO 999
      IF (RNID(I) .NE. F(1)) GO TO 4002
      LAMS(I)   = F(2)
      RNKD(I)   = F(3)
      RLMT(1,I) = F(4)
      RLMT(2,I) = F(5)
      RLMT(3,I) = F(6)
      GO TO 100
 4002 CONTINUE
      GO TO 999
C
  503 IF (N1 .NE. 32) GO TO 600
      DO 4003 I=1,NRNM
      IF (RNID(I) .EQ. 0.0) GO TO 999
      IF (RNID(I) .NE. F(1)) GO TO 4003
      IF (F(2) .NE. 0.0) RNLD1(I) = 0.693/F(2)
      RNQO1(I) = F(3)
      IF (F(4) .NE. 0.0) RNLDX(I) = 0.693/F(4)
      RNQOX(I) = F(5)
      GO TO 100
 4003 CONTINUE
      GO TO 999
C
C***** CC: 000 **********************************************************
C                                                                       *
C***** TYPE 50 CARD ENTERS AQUIFER FLOW SYSTEM DATA                     *
C                                                                       *
C***** CC: 000 **********************************************************
  600 IF (N1 .NE. 50) GO TO 700
C
      XA     = F(1)
      XS     = F(2)
      XKA    = F(3)
      XIA    = F(4)
      PORA   = F(5)
      AQAREA = F(6)
      VAQ    = XKA * XIA * AQAREA
      WTIME  = XA * PORA / (XKA * XIA)
      GO TO 100
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 51 CARD ENTERS HYDRAULIC GRADIENT DATA                     *
C                                                                      *
C***** CC: 000 *********************************************************
  700 IF (N1 .NE. 51) GO TO 740
C
      DO 741 I = 1,NCOF
      IF ( CVA(I) .NE. 0.0) GO TO 741
      ALPH(I) = F(1)
      CVA(I) = F(2)
      IF (F(3) .EQ. 0.0) GO TO 742
      CVC = F(3)
  742 CONTINUE
      GO TO 100
  741 CONTINUE
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 52 CARD ENTERS LEACH RATE, CANISTER LIFETIME, AND          *
C***** OTHER MISCELLANEOUS DATA                                        *
C                                                                      *
C***** CC: 000 *********************************************************
  740 IF (N1 .NE. 52) GO TO 750
C
      WFLR   = F(1)
      CLIFE  = F(2)
      VR     = F(3)
      TIC    = F(4)
      EXPECT = F(5)
      NTIC   = TIC
      GO TO 100
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** TYPE 53 CARD ENTERS DATA FOR EXPECTED RELEASES FROM             *
C***** A SALT REPOSITORY                                               *
C                                                                      *
C***** CC: 000 *********************************************************
  750 IF (N1 .NE. 53) GO TO 760
C
      TCLOS      = F(1)
      VMIN       = F(2)
      XHGH       = F(3)
      XLOW       = F(4)
      XILTH      = F(5)
      GO TO 100
```

```
C***** CC: 000 *******************************************************
C                                                                    *
C***** TYPE 60 CARD ENTERS ENVIRONMENTAL TRANSFER FACTORS            *
C                                                                    *
C***** CC: 000 *******************************************************
  760 IF (N1 .NE. 60) GO TO 800
C
      GLMS = F(1)
      LAMR = F(2)
      LAMG = F(3)
      LAMW = F(4)
      GO TO 100
C
C***** CC: 000 *******************************************************
C                                                                    *
C***** TYPE 70 CARD ENTERS OCEAN ENVIRONMENTAL PATHWAY DATA          *
C                                                                    *
C***** CC: 000 *******************************************************
  800 IF (N1 .NE. 70) GO TO 900
C
      S1I0 = F(1)
      S2I0 = F(2)
      TAU1 = F(3)
      TAU2 = F(4)
      GO TO 100
C
  900 IF (N1 .LT. 96) GO TO 999
      IF (N1 .EQ. 99) GO TO 998
      WRITE (6,21)
   21 FORMAT (1H ,9X,'ANOTHER PROBLEM WILL FOLLOW, BASED UPON THE ',
     1               'INPUTS TO THIS PROBLEM AND ANY PREVIOUS PROBLEMS')
      GO TO 190
C
  998 WRITE (6,20)
   20 FORMAT (1H ,9X,'INPUT DATA WAS CORRECTLY TERMINATED')
      GO TO 190
C
  999 CALL ERROR (5,N1,N2,F,A,IX)
      GO TO 100
C
  190 IF (IPATH .EQ. 1) GO TO 194
C
C***** CC: 000 ********************************************************
C                                                                     *
C***** EERF TAPES 3 ∂ 4 READ IN HEALTH EFFECTS FACTORS                *
C                                                                     *
C***** CC: 000 ********************************************************
C
```

```
      READ (3,15,ERR=999)         (HFSTIT(I),I=1,19)
      IPATH = 1
  188 READ (3,14,ERR=999,END=192) (F(I),I=1,13)
   15 FORMAT (1X,19A4)
   14 FORMAT (1X,F8.3,1P6E10.3/1X,1P6E10.3)
C
      DO 1600 I=1,NRNM
      IF (RNID(I) .EQ. 0.0) GO TO 188
      IF (RNID(I) .NE. F(1)) GO TO 1600
C
      HFS1 (I) = F( 2)
      HFS2 (I) = F( 3)
      HFS3 (I) = F( 4)
      HFS4 (I) = F( 5)
      HFS5 (I) = F( 6)
      HFS6 (I) = F( 7)
      HFS7 (I) = F( 8)
      HFS8 (I) = F( 9)
      HFS9 (I) = F(10)
      HFS10(I) = F(11)
      HFS11(I) = F(12)
      HFS12(I) = F(13)
      GO TO 188
 1600 CONTINUE
      GO TO 188
C
  192 READ (4,15,ERR=999)         (HFGTIT(I),I=1,19)
  189 READ (4,14,ERR=999,END=193) (F(I),I=1,13)
C
      DO 1700 I=1,NRNM
      IF (RNID(I) .EQ. 0.0) GO TO 189
      IF (RNID(I) .NE. F(1)) GO TO 1700
C
      HFG1 (I) = F( 2)
      HFG2 (I) = F( 3)
      HFG3 (I) = F( 4)
      HFG4 (I) = F( 5)
      HFG5 (I) = F( 6)
      HFG6 (I) = F( 7)
      HFG7 (I) = F( 8)
      HFG8 (I) = F( 9)
      HFG9 (I) = F(10)
      HFG10(I) = F(11)
      HFG11(I) = F(12)
      HFG12(I) = F(13)
      GO TO 189
 1700 CONTINUE
      GO TO 189
C
```

```
  193 REWIND 3
      REWIND 4
C
  194 DO 1800 I=1,NRN
      IF (HFS1(I) .NE. 0.0) GO TO 1800
      WRITE (6,67) RNDS1(I),RNDS2(I)
   67 FORMAT (10X,'NO DATA WAS ENTERED FOR',2A4)
      IX = 1
 1800 CONTINUE
C
      IF (IX .NE. 1) GO TO 191
      WRITE (6,40)
   40 FORMAT (1H ,'PROBLEM TERMINATED DUE TO INPUT ERRORS')
      STOP 1001
C
C***** CC: 000 ********************************************************
C                                                                     *
C***** SET UP NPRT AND NOUT(I) FOR OUTPUT FORMATS BASED UPON NEVT    *
C***** NEVT = NUMBER OF EVENT TIMES                                   *
C                                                                     *
C***** CC: 000 ********************************************************
C
  191 IF (NEVT .GT. 8) GO TO 140
      NPRT = 1
      NOUT(1) = NEVT
      GO TO 195
  140 DO 1101 I=2,NOUT8
      NK = NEVT / I
      IF (NK .GT. 8) GO TO 1101
      NR = NEVT - I * NK
      NPRT = I
  143 IF (NR .GT. 0) GO TO 141
      DO 1102 J=1,NPRT
 1102 NOUT(J) = NK
      GO TO 195
  141 IF (NK .GE. 8) GO TO 142
      DO 1103 J=1,NPRT
      NOUT(J) = NK + 1
      NR = NR - 1
      IF (NR .GT. 0) GO TO 1103
      JJ = J + 1
      DO 1104 K=JJ,NPRT
 1104 NOUT(K) = NK
      GO TO 195
 1103 CONTINUE
      CALL ERROR (8,NPRT,NEVT,F,A,IX)
  142 NPRT = I + 1
      NK = NEVT / NPRT
      NR = NEVT - NPRT * NK
      GO TO 143
 1101 CONTINUE
  195 CONTINUE
C
      DO 7002 I=1,NEVT
      IF (I .NE. 1) GO TO 145
      TEVNT(I) = TOBND(I) / 2.0
      GO TO 7002
  145 TEVNT(I) = (TOBND(I) + TOBND(I-1)) / 2.0
 7002 CONTINUE
C
      DO 7088 I = 1,NEVS
      DO 1063 NA = 1,NDCT
      AMEAN1(NA,I) = 0.0
      DO 1060 J=1,NEVT
      IF ( TOBND(J) .GT. TEDC(NA) ) GO TO 1060
      IF ( NA .EQ. 1 ) GO TO 1064
 1064 CONTINUE
      IF (J .NE. 1) GO TO 1061
      TBAND = TOBND(J)
      GO TO 1062
 1061 TBAND = TOBND(J) - TOBND(J-1)
      IF (FRATE(I,J) .EQ. 0.0) FRATE(I,J) = FRATE(I,J-1)
      IF (FRATE(I,J) .LT. 0.0) FRATE(I,J) = 0.0
 1062 CA = TBAND * FRATE(I,J)
      IF (NEVTT(I) .EQ. 2 .AND. TOBND(J) .LE. TIC) CA = 0.0
      IF (NEVTT(I) .EQ. 3 .AND. TOBND(J) .LE. TIC) CA = 0.0
      AMEAN1(NA,I) = AMEAN1(NA,I) + CA
 1060 CONTINUE
 1063 CONTINUE
 7088 CONTINUE
      DO 7003 I=1,NEVS
      IF (PROB(I,1) .NE. 0.0) GO TO 7003
      DO 7004 J=1,NEVT
      IF (J .NE. 1) GO TO 146
      TBAND = TOBND(J)
      GO TO 147
  146 TBAND = TOBND(J) - TOBND(J-1)
      IF (FRATE(I,J) .EQ. 0.0) FRATE(I,J) = FRATE(I,J-1)
      IF (FRATE(I,J) .LT. 0.0) FRATE(I,J) = 0.0
  147 CA = TBAND * FRATE(I,J)
      IF (NEVTT(I) .EQ. 2 .AND. TOBND(J) .LE. TIC) CA = 0.0
      IF (NEVTT(I) .EQ. 3 .AND. TOBND(J) .LE. TIC) CA = 0.0
      IF (CA .GT. 0.04) GO TO 148
      PROB(I,J) = CA
      GO TO 7004
  148 IF (CA .LT. 100.0) GO TO 149
      PROB(I,J) = 1.0
      GO TO 7004
  149 PROB(I,J) = 1.0 - EXP (-CA)
 7004 CONTINUE
 7003 CONTINUE
C
```

```
      DO 7001 J=1,NEVTM
 7001 NENTT(J) = TEVNT(J)
C
      DO 7005 I=1,NRN
      IF (RNQOX(I) .EQ. 0.0) RNQOX(I) = RNQO(I)
      IF (RNLDX(I) .EQ. 0.0) RNLDX(I) = RNLD(I)
      IF (LR(I)    .EQ. 0.0) LR(I)    = WFLR
      IF (LAMS(I)  .EQ. 0.0) LAMS(I)  = GLMS
      OLMT  = 0.0
      DO 7007 J=1,3
 7007 IF (RLMT(J,I) .NE. 0.0) OLMT = RLMT(J,I)
      IF (OLMT .EQ. 0.0) OLMT = 1.0
      DO 7008 J=1,3
 7008 IF (RLMT(J,I) .EQ. 0.0) RLMT(J,I) = OLMT
 7005 IF (RLMT(1,I) .NE. 1.0) IRLMT = 0
C
      DO 1245 I = 1,NCOF
      IF ( ALPH(I) .EQ. 0. ) ALPH(I) = 1.0
 1245 CONTINUE
      DO 7006 I=1,NEVS
      IF (VTANK(I) .EQ. 0.0) VTANK(I) = VR
      IF (VDRILL(I) .EQ. 0.0) VDRILL(I) = VTANK(I)
 7006 IF (FTANK(I) .EQ. 0.0) FTANK(I) = 1.0
C
      NCT = NEVT * NEVS
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** START DOSE COMMITMENT TIME LOOP (1000)                          *
C***** SUBSCRIPT = NA                                                  *
C                                                                      *
C***** CC: 000 *********************************************************
C
  350 DO 1000 NA=1,NDCT
C
      IEX = 0
      TA  = 0.0
      NTA = 0
      NTE = TEDC(NA)
      TC  = TEDC(NA)
      IF (NA .EQ. 1 .OR. NDOT .EQ. 1) GO TO 196
      TA  = TEDC(NA-1)
      NTA = TA
  196 IF (TDINT .NE. 0.0) GO TO 197
      TB  = TEDC(NA)
      NTB = NTE
      GO TO 198
  197 IF (TEDC(NA) .GT. TDINT) CALL ERROR (25,N1,N1,F,A,IX)
      TB  = TDINT
      NTB = TB
C
```

```
  198 DO 1236 I=1,NEVTM
      DO 1236 J=1,NEVSM
      NDEVS(J,I) = 0
      CNS(J,I)  = 0.0
      CNG(J,I)  = 0.0
      CNR(J,I)  = 0.0
      NRSMX(J,I)= 0.0
      NRGMX(J,I)= 0.0
      NRRMX(J,I)= 0.0
      DO 1236 K=1,NRNM
      CNSR(J,I,K) = 0.0
      CNGR(J,I,K) = 0.0
 1236 CNRR(J,I,K) = 0.0
      DO 1237 I = 1,NEVSM
 1237 NDCASE(I) = 0
C
C***** CC: 000 **********************************************************
C                                                                       *
C***** START EVENT (3000) AND EVENT TIME (2000) LOOPS                   *
C***** SUBSCRIPTS = NC AND NB                                           *
C                                                                       *
C***** CC: 000 **********************************************************
C
      DO 3000 NC=1,NEVS
      DO 2000 NB=1,NEVT
C
      IF (TEVNT(NB) .GT. TEDC(NA)) GO TO 2000
C
C
      CONSM = 0.0
      CONGM = 0.0
      CONRM = 0.0
      CONST = 0.0
      CONGT = 0.0
      CONRT = 0.0
C
C***** CC: 000 **********************************************************
C                                                                       *
C                             EVENT BRANCHING                           *
C***** BRANCH TO METEORITE, VOLCANO, DRILLING DIRECT IMPACT (110),      *
C***** NO HIT DRILLING (111), FAULTING, BRECCIA PIPES (112),            *
C***** OR NORMAL GROUNDWATER FLOWS - NONSALT (113) OR SALT (117)        *
C                                                                       *
C***** CC: 000 **********************************************************
      NGA = NEVTT(NC)
      GO TO (110,110,111,112,113), NGA
      CALL ERROR (9,NEVTT(NC),NC,F,A,IX)
C
```

```
C***** CC: 000 *********************************************************
C                                                                      *
C***** BRANCH 110                                                      *
C***** START RADIONUCLIDE LOOP (4100) FOR METEORITES, VOLCANOES,       *
C***** AND DRILLING DIRECT IMPACT                                      *
C                                                                      *
C***** CC: 000 *********************************************************
C
  110 DO 4100 ND=1,NRN
C
      SF1 = S1I0 * RNKD(ND)
      SF2 = S2I0 * RNKD(ND)
C
      NGB = NRNTY(ND)
      GO TO (150,151), NGB
      CALL ERROR (20,NRNTY(ND),ND,F,A,IX)
C
  150 CA = RNLD(ND) * TEVNT(NB)
      IF (CA .GE. 20.0) GO TO 4100
      CA = EEXP (-CA,IEX)
      QALS = FHIT(NC) * RNQO(ND) * CA
      GO TO 159
C
  151 CA = RNLD(ND) * TEVNT(NB)
      CA1 = RNLD1(ND) * TEVNT(NB)
      CA = EEXP (-CA,IEX)
      CA1 = EEXP (-CA1,IEX)
      CB = RNLD(ND) / (RNLD(ND) - RNLD1(ND))
      QALS = FHIT(NC) * (CB * RNQO1(ND) * (CA1 - CA) + RNQO(ND) * CA)
      IF (QALS .EQ. 0.0) GO TO 4100
C
  159 IF (NGA .EQ. 2) GO TO 152
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** BRANCH 110                                                      *
C***** AIR PATHWAY CALCULATIONS FOR METEORITES AND VOLCANOES           *
C                                                                      *
C***** CC: 000 *********************************************************
C
      CALL SMESS1
     1    (RNLD(ND),LAMG,LAMS(ND),LAMR,TEVNT(NB),TB,MESS1N,MESSA,IEX)
      TF3 = TFAC3 (RNLD(ND),LAMS(ND),TEVNT(NB),TB,IEX)
      TF4 = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TB,IEX)
      TF5 = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TB,IEX)
      TF6 = SMESSN (RNLD(ND),LAMW,SF1,SF2,TAU1,TAU2,TEVNT(NB),TB,IEX)
C
      IF (TA .GT. TEVNT(NB)) GO TO 153
C
```

```
      CONS = QALS * (FAL * HFS7(ND) * MESS1N + FAL * HFS8(ND) * MESSA
     1              + FLL * HFS9(ND) * TF3    + FLL * HFS10(ND) * TF4
     2              + FLL * HFS11(ND) * TF5   + FAW * HFS12(ND) * TF6)
      CONG = QALS * (FAL * HFG7(ND) * MESS1N + FAL * HFG8(ND) * MESSA
     1              + FLL * HFG9(ND) * TF3    + FLL * HFG10(ND) * TF4
     2              + FLL * HFG11(ND) * TF5   + FAW * HFG12(ND) * TF6)
      CONR = QALS / RLMT(1,ND)
      GO TO 154
C
  153 CALL SMESS1
     1     (RNLD(ND),LAMG,LAMS(ND),LAMR,TEVNT(NB),TA,MESS1A,MESSAA,IEX)
      TF3A = TFAC3 (RNLD(ND),LAMS(ND),TEVNT(NB),TA,IEX)
      TF4A = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TA,IEX)
      TF5A = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TA,IEX)
      TF6A = SMESSN (RNLD(ND),LAMW,SF1,SF2,TAU1,TAU2,TEVNT(NB),TA,IEX)
C
      CONS = QALS * (FAL * HFS7(ND) * (MESS1N - MESS1A)
     1             +  FAL * HFS8(ND) * (MESSA - MESSAA)
     2             +  FLL * HFS9(ND) * (TF3 - TF3A)
     3             +  FLL * HFS10(ND) * (TF4 - TF4A)
     4             +  FLL * HFS11(ND) * (TF5 - TF5A)
     5             +  FAW * HFS12(ND) * (TF6 - TF6A))
      CONG = QALS * (FAL * HFG7(ND) * (MESS1N - MESS1A)
     1             +  FAL * HFG8(ND) * (MESSA - MESSAA)
     2             +  FLL * HFG9(ND) * (TF3 - TF3A)
     3             +  FLL * HFG10(ND) * (TF4 - TF4A)
     4             +  FLL * HFG11(ND) * (TF5 - TF5A)
     5             +  FAW * HFG12(ND) * (TF6 - TF6A))
      CONR = QALS / RLMT(1,ND)
      GO TO 154
C
C***** CC: 000 *******************************************************
C                                                                    *
C***** BRANCH 110                                                    *
C***** LAND SURFACE PATHWAY CALCULATIONS FOR DRILLING DIRECT IMPACT  *
C                                                                    *
C***** CC: 000 *******************************************************
C
  152 TF3 = TFAC3 (RNLD(ND),LAMS(ND),TEVNT(NB),TB,IEX)
      TF4 = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TB,IEX)
      TF5 = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TB,IEX)
      IF (TA .GT. TEVNT(NB)) GO TO 155
C
      CONS = QALS * (HFS4(ND) * TF3 + HFS5(ND) * TF4 + HFS6(ND) * TF5)
      CONG = QALS * (HFG4(ND) * TF3 + HFG5(ND) * TF4 + HFG6(ND) * TF5)
      CONR = QALS / RLMT(2,ND)
      GO TO 154
C
  155 TF3A = TFAC3 (RNLD(ND),LAMS(ND),TEVNT(NB),TA,IEX)
      TF4A = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TA,IEX)
      TF5A = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TEVNT(NB),TA,IEX)
C
```

```
      CONS = QALS * (HFS4(ND) * (TF3 - TF3A) + HFS5(ND) * (TF4 - TF4A)
     1             + HFS6(ND) * (TF5 - TF5A))
      CONG = QALS * (HFG4(ND) * (TF3 - TF3A) + HFG5(ND) * (TF4 - TF4A)
     1             + HFG6(ND) * (TF5 - TF5A))
      CONR = QALS / RLMT(2,ND)
C
  154 IF (CONS .LE. CONSM) GO TO 166
      CONSM = CONS
      NRSMX(NC,NB) = ND
C
  166 IF (CONG .LE. CONGM) GO TO 167
      CONGM = CONG
      NRGMX(NC,NB) = ND
C
  167 IF (CONR .LE. CONRM) GO TO 168
      CONRM = CONR
      NRRMX(NC,NB) = ND
C
  168 CONST  = CONST + CONS
      CONGT  = CONGT + CONG
      CONRT  = CONRT + CONR
C
      CNSR(NC,NB,ND) = CONS
      CNGR(NC,NB,ND) = CONG
      CNRR(NC,NB,ND) = CONR
C
 4100 CONTINUE
      CNS(NC,NB) = CONST
      CNG(NC,NB) = CONGT
      CNR(NC,NB) = CONRT
      GO TO 2000
C
C***** CC: 000 *******************************************************
C                                                                    *
C***** BRANCH 113 a 112                                              *
C***** NORMAL GROUNDWATER FLOWS - NONSALT (113) AND FAULTING OR      *
C***** BRECCIA PIPE EVENTS (112)                                     *
C                                                                    *
C***** CC: 000 *******************************************************
C
  113 IF (IREP .EQ. 1) GO TO 117
      IF (NB .GT. 1) GO TO 2000
  112 FRAC = FTANK(NC) - FHIT(NC)
C
      V = VTANK(NC)
      TFAIL = TEVNT(NB)
C
      IF (CLIFE .GE. TFAIL) TFAIL = CLIFE
C
C
```

```
      VX = VOLFLO(IEX,TFAIL)
      VY = AREA(NC) * K1(NC)
      VX = VX * VY
C
      TDEL1  = TDELI(XS,TFAIL,PORS(NC),K1(NC),IEX,TB)
      TDEL1A = TDELI(XS,TEVNT(NB),PORS(NC),K1(NC),TB)
      TB1 = TB
C
C
C***** CC: 000 *******************************************************
C                                                                    *
C     112 LOOP FOR FAULTING AND BRECCIA PIPE EVENTS                  *
C***** BRANCH 112                                                    *
C***** START RADIONUCLIDE LOOP (4000) FOR 112 BRANCH                 *
C                                                                    *
C***** CC: 000 *******************************************************
C
      DO 4000 ND=1,NRN
C
      TSOL = 0.
      TVAQ = TFAIL
      AMT = FRAC * RNQOX(ND)
      BOXS  = 0.0
      BOXG  = 0.0
      BOXR  = 0.0
      PIPES = 0.0
      PIPEG = 0.0
      PIPER = 0.0
      TDEL2 = TFAIL + RNDA(ND) * WTIME
C
      TDEL = TDEL1 + TDEL2
      TMAX = TB1 - TDEL + TFAIL
      TMIN = TFAIL
C
      IF (VX .LE. VAQ) GO TO 5102
C
      TVAQ = EQUAL (VY,VAQ,NT,TMAX,TMIN,IEX)
 5102 CONTINUE
C
      IF (TDEL .GT. TB) GO TO 4050
      IF (TDEL * RNLDX(ND) .GT.  20.0) GO TO 4050
      IF(RNSOL(ND) .EQ. 0.0) GO TO 846
C
C***** CC: 000 *******************************************************
C                                                                    *
C***** BRANCH 112                                                    *
C***** TSOL IS CALCULATED                                            *
C***** TSOL IS WHEN THE RADIONUCLIDE CONCENTRATION BECOMES           *
C*****        LOWER THAN ITS SOLUBILITY LIMIT                        *
C                                                                    *
C***** CC: 000 *******************************************************
C
```

```
      TSOL = -1.0
      DEL = 100.
      NOON =(TMAX - TFAIL) / DEL
      Y1 = 0.0
      CHECK = AMT / V
      IF ( CHECK .LE. RNSOL(ND)) GO TO 847
      IF ( TFAIL .EQ. CLIFE ) GO TO 5105
      TG = TFAIL - CLIFE
      CHECK2 = CHECK * EEXP(-RNLDX(ND) * TFAIL,IEX)
      CHECK2 = CHECK2 * (1. - EEXP(-LR(ND) * TG, IEX))
      IF (CHECK2 .LE. RNSOL(ND) ) GO TO 847
 5105 NX = NOON + 2
      DO 840 K=1,NX
      T1 = TFAIL + DEL * (K-2)
      IF( T1 * RNLDX(ND) .GT. 20.0) GO TO 847
      IF(K .EQ. 1) T1 = TFAIL
      IF(K .EQ. 2) T1 = TFAIL + 10.
      IF(Y1 .NE. 0.) GO TO 842
      IF(T1 .GE. TVAQ) GO TO 852
      CX = CONVQ(T1,IEX,VAQ,RNSOL(ND),RNLDX(ND),AMT,V,
     1           CLIFE,TFAIL,TVAQ,AREA(NC),K1(NC),LR(ND))
      IF(CX .LT. RNSOL(ND)) GO TO 840
      IF ( K .LE. 2 ) GO TO 845
      K = K - 1
      T1 = T1 - DEL
  845 CONTINUE
      Y1 = 1.0
      TSOLI = T1
      GO TO 840
  852 IF(K .LE. 2) GO TO 859
C     A8 = MOD(K,10)
C     IF(A8 .NE. 0.) GO TO 840
  859 IF(T1 .GT. 10000.) GO TO 860
      CX = CONVT(T1,VAQ,RNSOL(ND),RNLDX(ND),AMT,V,
     1           CLIFE,TFAIL,TVAQ,AREA(NC),K1(NC),LR(ND))
  860 IF(T1 .GT. 10000.) CX = CONHYD(T1,IEX,RNSOL(ND),RNLDX(ND),AMT,V,
     1                   CLIFE,TFAIL,TVAQ,AREA(NC),K1(NC),LR(ND))
      IF(CX .LT. RNSOL(ND)) GO TO 840
      IF ( K .LE. 2 ) GO TO 849
      K = K - 1
      T1 = T1 - DEL
  849 CONTINUE
      Y1 = 1.0
      TSOLI = T1
      GO TO 840
  842 IF(T1 .GE. TVAQ) GO TO 843
      TSOL = VQSOL(T1,IEX,VAQ,RNSOL(ND),RNLDX(ND),AMT,V,
     1           CLIFE,TFAIL,TVAQ,AREA(NC),K1(NC),LR(ND))
      IF(TSOL .EQ. -1.0) GO TO 840
      GO TO 846
  843 TSOL = VTSOL(T1,IEX,VAQ,RNSOL(ND),RNLDX(ND),AMT,V,
     1              CLIFE,TFAIL,TVAQ,AREA(NC),K1(NC),LR(ND))
      IF(TSOL .EQ. -1.0) GO TO 840
      GO TO 846
  840 CONTINUE
  847 IF(Y1 .EQ. 1.0) TSOL = TB1
      IF(Y1 .EQ. 0.0) TSOL = TFAIL
  846 CONTINUE
C
C***** CC: 000 *************************************************************
C                                                                          *
C***** BRANCH 112                                                          *
C***** CONSEQUENCES CALCULATED AS CURIES RELEASED a HEALTH EFFECTS         *
C                                                                          *
C***** CC: 000 *************************************************************
C
C
      SOL = RNSOL(ND)
      IF ( TSOL .EQ. TFAIL .AND. Y1 .EQ. 0. ) SOL = 0.
      IF ( TSOL .LT. TFAIL ) SOL = 0.
      TMAX = TB1 - TDEL + TFAIL
      IF ( TMAX .GT. TSOL .AND. SOL .NE. 0. ) TMAX = TSOL
C
      IF (TA .GT. TDEL) TMIN = TA - TDEL + TFAIL
      IF (TA - TDEL + TFAIL .GT. TVAQ) TVAQ = TA - TDEL + TFAIL
      X8 = 0.0
      Y8 = 0.
      IF (SOL .NE. 0.0) GO TO 5103
C
      IF (TFAIL .EQ. TVAQ) GO TO 5250
C
      X8 = ENT1A (TVAQ,TMIN,VAQ,CLIFE,LR(ND),V,TFAIL,RNLDX(ND),AMT,IEX)
C
 5250 IF (TVAQ .EQ. TMAX) GO TO 5104
C
      Y8 = SALT (VY,LR(ND),V,TFAIL,TVAQ,TMAX,NN,IEX,CLIFE,AMT,RNLDX(ND),
     1              VAQ)
      GO TO 5104
C
 5103 TV = TVAQ
      IF ( TVAQ .GT. TMAX ) TV = TMAX
      IF ( TMAX .LE. TFAIL ) TV = TFAIL
      X8 = VAQ * SOL * (TV - TFAIL)
      IF ( TVAQ .GE. TMAX ) GO TO 5104
      Y8 = ENTCO (VY,SOL,TMAX,TVAQ,IEX)
 5104 Z = -RNLDX(ND) * (TDEL - TFAIL)
      Z = EEXP (Z,IEX)
      QSW = (X8 + Y8) * Z
C
```

```
      BOXS = QSW * (HFS1(ND) + HFS2(ND) / (LAMS(ND) + RNLDX(ND)))
      BOXG = QSW * (HFG1(ND) + HFG2(ND) / (LAMS(ND) + RNLDX(ND)))
      BOXR = QSW / RLMT(3,ND)
C
 4050 IF ( FHIT(NC) .EQ. 0. ) GO TO 4051
      TDEL2 = TEVNT(NB) + RNDA(ND) * WTIME
      TDEL = TDEL1A + TDEL2
C
      IF (TDEL * RNLDX(ND) .GT.  20.0) GO TO 4000
      IF (TDEL .GT. TB1) GO TO 4000
C
      TMAX = TB1 - TDEL + TEVNT(NB)
      TMIN = TEVNT(NB)
C
 5199 Y1 = -RNLDX(ND) * TEVNT(NB)
      Y1 = EEXP (Y1,IEX)
      IF (TA .GT. TDEL) TMIN = TA - TDEL + TEVNT(NB)
      IF (TA - TDEL + TEVNT(NB) .GT. TVAQ) TVAQ = TA - TDEL + TEVNT(NB)
C
      X10 = LR(ND) * TEVNT(NB)
      X10 = EEXP (X10,IEX)
      X10 = X10 * LR(ND) * FHIT(NC) * RNQOX(ND) / (LR(ND) + RNLDX(ND))
      X8 = -TMIN * (LR(ND) + RNLDX(ND))
      X8 = EEXP (X8,IEX)
      Y8 = -TMAX * (LR(ND) + RNLDX(ND))
      Y8 = -EEXP (Y8,IEX)
      X8 = X8 * X10
      Y8 = Y8 * X10
 5106 Z = -RNLDX(ND) * (TDEL - TEVNT(NB))
      Z = EEXP (Z,IEX)
      QSW = (X8 + Y8) * Z
C
      PIPES = QSW * (HFS1(ND) + HFS2(ND) / (LAMS(ND) + RNLDX(ND)))
      PIPEG = QSW * (HFG1(ND) + HFG2(ND) / (LAMS(ND) + RNLDX(ND)))
      PIPER = QSW / RLMT(3,ND)
C
 4051 CONS  = BOXS + PIPES
      CONG  = BOXG + PIPEG
      CONR  = BOXR + PIPER
C
      IF (CONS .LE. CONSM) GO TO 131
      CONSM = CONS
      NRSMX(NC,NB) = ND
  131 IF (CONG .LE. CONGM) GO TO 132
      NRGMX(NC,NB) = ND
      CONGM = CONG
  132 IF (CONR .LE. CONRM) GO TO 133
      CONRM = CONR
      NRRMX(NC,NB) = ND
  133 CONST  = CONST + CONS
      CONGT  = CONGT + CONG
      CONRT  = CONRT + CONR
C
      CNSR(NC,NB,ND) = CONS
      CNGR(NC,NB,ND) = CONG
      CNRR(NC,NB,ND) = CONR
C
 4000 CONTINUE
C
      CNS(NC,NB) = CONST
      CNG(NC,NB) = CONGT
      CNR(NC,NB) = CONRT
C
 2000 CONTINUE
C
      GO TO 3000
C
C***** CC: 000 *******************************************************
C                                                                   *
C***** BRANCH 111                                                   *
C***** NO HIT DRILLING EVENTS(111)  - PROBABILITIES                 *
C                                                                   *
C***** CC: 000 *******************************************************
  111 AMEAN = AMEAN1(NA,NC)
      TIC1 = TIC
      IF ( TC .EQ. TIC1 ) P = 0.
      IF ( TC .EQ. TIC1 ) GO TO 1528
      P = AMEAN1(NA,NC) / (TC - TIC1)
 1528 SIGMA = AMEAN * (1.0 - P)
      SIGMA = SQRT (SIGMA)
      IX = 12
      IF (AMEAN .GT. 6.00) GO TO 1529
      X8 = 3.0 * SIGMA + AMEAN
      IX = INT (X8)
      IF (AMEAN .LT. 0.5) IX = 3
      IX = IX + 1
 1529 RR = 0.0
C
      DO 5000 I=1,IX
      IF (AMEAN .GT. 6.00) GO TO 5015
      R = I - 1.0
      NOC = I - 1
      PROB(NC,I) = BINOM (TC,R,P)
      GO TO 5001
 5015 RL = AMEAN + SIGMA * (I - 7) * .5
      IF (RL .LT. 0.) RL = 0.
      IF (RR .GT. 0.0) RL = RR
      RR = AMEAN + SIGMA * (I - 6) * .5
      IF (RR .LT. 0.) RR = 0.
      RM = (RL + RR) / 2.0
      IM = INT (RM)
      RM = IM
      NOC = IM
      IF(I .EQ. 1  .OR.  I .EQ. 12)  X8 = .005
      IF(I .EQ. 2  .OR.  I .EQ. 11)  X8 = .0165
      IF(I .EQ. 3  .OR.  I .EQ. 10)  X8 = .050
      IF(I .EQ. 4  .OR.  I .EQ. 9)  X8 = .090
      IF(I .EQ. 5  .OR.  I .EQ. 8)  X8 = .150
      IF(I .EQ. 6  .OR.  I .EQ. 7)  X8 = .190
C
      PROB(NC,I) = X8
 5001 NDCASE(NC) = IX
      IF (AMEAN .GT. 6.) GO TO 5026
      IF (NOC .EQ. 0) GO TO 5025
 5026 CONST = 0.0
      CONGT = 0.0
      CONRT = 0.0
      NOCT = NOC
      IF (AMEAN .LE. 6.) GO TO 5002
      NOCT = INT(AMEAN)
      IF (I .GT. 1) GO TO 5003
 5002 XX = TIC1
      X1 = NOCT + 1.0
      DEL = (TC - TIC1) / X1
C
C
C***** CC: 000 ********************************************************
C                                                                     *
C***** BRANCH 111                                                     *
C***** NO HIT DRILLING EVENTS - RELEASES TO LAND SURFACE              *
C***** CONSEQUENCES CALCULATED AS CURIES RELEASED a HEALTH EFFECTS    *
C                                                                     *
C***** CC: 000 ********************************************************
C
      DO 5005 J=1,NOCT
      XX = XX + DEL
      TDRILL = XX
C
      IF (CLIFE .GE. TDRILL) GO TO 5005
C
      DO 5006 ND=1,NRN
      IF (TDRILL * RNLD(ND) .GT. 20.0) GO TO 5006
      NGB = NRNTY(ND)
      FRINV = FTANK(NC) * RNQO(ND)
C
      CA = TANK (VTANK(NC),LR(ND),CLIFE,TDRILL,FRINV,RNLD(ND),IEX)
C
      IF ( NGB .EQ. 1 ) GO TO 1500
      CAD = DTANK (VTANK(NC),LR(ND),CLIFE,TDRILL,FTANK(NC),RNQO(ND),
     1           RNLD(ND),RNQO1(ND),RNLD1(ND),IEX)
C
      CA = CA + CAD
 1500 IF (RNSOL(ND) .EQ. 0.0) GO TO 1901
C
      IF (CA .GT. RNSOL(ND)) CA = RNSOL(ND)
 1901 QALS = CA * VTANK(NC)
      IF (QALS .EQ. 0.0) GO TO 5006
      QALS = QALS * VDRILL(NC) / VTANK(NC)
C
      TF3 = TFAC3 (RNLD(ND),LAMS(ND),TDRILL,TB,IEX)
      TF4 = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TDRILL,TB,IEX)
      TF5 = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TDRILL,TB,IEX)
C
      IF (TA .GT. TDRILL) GO TO 1550
C
      CONS = QALS * (HFS4(ND) * TF3 + HFS5(ND) * TF4 + HFS6(ND) * TF5)
      CONG = QALS * (HFG4(ND) * TF3 + HFG5(ND) * TF4 + HFG6(ND) * TF5)
      CONR = QALS / RLMT(2,ND)
      GO TO 1540
C
 1550 TF3A = TFAC3 (RNLD(ND),LAMS(ND),TDRILL,TA,IEX)
      TF4A = TFAC4 (RNLD(ND),LAMS(ND),LAMR,TDRILL,TA,IEX)
      TF5A = TFAC5 (RNLD(ND),LAMS(ND),LAMR,TDRILL,TA,IEX)
C
      CONS = QALS * (HFS4(ND) * (TF3 - TF3A) + HFS5(ND) * (TF4 - TF4A)
     1             + HFS6(ND) * (TF5 - TF5A))
      CONG = QALS * (HFG4(ND) * (TF3 - TF3A) + HFG5(ND) * (TF4 - TF4A)
     1             + HFG6(ND) * (TF5 - TF5A))
      CONR = QALS / RLMT(2,ND)
C
 1540 CONST = CONST + CONS
      CONGT = CONGT + CONG
      CONRT = CONRT + CONR
C
      CSR(J,ND) = CONS
      CGR(J,ND) = CONG
      CRR(J,ND) = CONR
C
 5006 CONTINUE
 5005 CONTINUE
C
      IF (IDRILL .EQ. 1) GO TO 5025
C
```

```
C***** CC: 000 *********************************************************
C                                                                      *
C***** BRANCH 111                                                      *
C***** NO HIT DRILLING - RELEASES TO GROUNDWATER                       *
C***** CONSEQUENCES CALCULATED AS CURIES RELEASED a HEALTH EFFECTS    *
C                                                                      *
C***** CC: 000 *********************************************************
C
      XX = TIC1
  504 DO 5007 J=1,NOCT
      XX = XX + DEL
      TDRILL = XX
C
      IF (CLIFE .GE. TDRILL) TDRILL = CLIFE
C
      AA =  AREA(NC)
C
      TDEL1 = TDELKI (XS,TDRILL,PORS(NC),K1(NC),KPRIM(NC),IEX,TB)
C
      DO 5008 ND=1,NRN
C
      TDEL2 = RNDA(ND) * WTIME + TDRILL
      TDEL = TDEL1 + TDEL2
C
      IF (TDEL .GT. TB) GO TO 5008
      IF (TDEL * RNLD(ND) .GT.  20.0) GO TO 5008
C
      TI = TDRILL
      IF (TA .GT. TDEL) TI = TA - TDEL + TDRILL
      Q = FTANK(NC) * RNQOX(ND) * EEXP(-RNLDX(ND)*TDRILL,IEX)/VTANK(NC)
      IF ( Q .LT. RNSOL(ND) ) GO TO 5008
C
      IF (RNSOL(ND) .EQ. 0.0) GO TO 5009
      TSOL = TSOLDR (VTANK(NC),LR(ND),CLIFE,RNQO(ND),RNLD(ND),
     1               FTANK(NC),TB,TI,RNSOL(ND),IEX)
      TF = TB - TDEL + TDRILL
      IF (TSOL .EQ. -1.) GO TO 5009
      IF ( TF .GT. TSOL ) TF = TSOL
C
      QSW = ENTANK (AA,K1(NC),KPRIM(NC),0.0,RNSOL(ND),1.0,TF,TI,0.0,
     1              CLIFE,IEX,NN)
C
      GO TO 5020
C
 5009 CONTINUE
C
      QSW = ENTANK (AA,K1(NC),KPRIM(NC),RNLD(ND),RNQOX(ND),VTANK(NC),
     1              TF,TI,LR(ND),CLIFE,IEX,NN)
 5020 Y8 = -RNLD(ND) * (TDEL - TDRILL)
C
      QSW = QSW * EEXP (Y8,IEX)
C
```

```
      CONS = QSW * (HFS1(ND) + HFS2(ND) / (LAMS(ND) + RNLDX(ND)))
      CONG = QSW * (HFG1(ND) + HFG2(ND) / (LAMS(ND) + RNLDX(ND)))
      CONR = QSW / RLMT(3,ND)
C
      CONST = CONST + CONS
      CONGT = CONGT + CONG
      CONRT = CONRT + CONR
C
      CSR(J,ND) = CONS + CSR(J,ND)
      CGR(J,ND) = CONG + CGR(J,ND)
      CRR(J,ND) = CONR + CRR(J,ND)
C
 5008 CONTINUE
 5007 CONTINUE
C
 5025 CNS(NC,I) = CONST
      CNG(NC,I) = CONGT
      CNR(NC,I) = CONRT
      CNSX = CONST
      CNGX = CONGT
      CNRX = CONRT
      DO 4998 ND = 1,NRN
          NOCM = NOCT - 1
      DO 4999 J = 1,NOCM
          CSR(NOCT,ND) = CSR(J,ND) + CSR(NOCT,ND)
          CGR(NOCT,ND) = CGR(J,ND) + CGR(NOCT,ND)
          CRR(NOCT,ND) = CRR(J,ND) + CRR(NOCT,ND)
 4999 CONTINUE
 4998 CONTINUE
C
 5003 NDEVS(NC,I) = NOC
C
 5000 CONTINUE
C
      IF (AMEAN .LE. 6.0) GO TO 5004
      DO 6111 I = 1,IX
      X1X = NDEVS(NC,I)
      FX1X = X1X / INT(AMEAN)
      CNS(NC,I) = CNSX * FX1X
      CNG(NC,I) = CNGX * FX1X
 6111 CNR(NC,I) = CNRX * FX1X
      DO 4997 ND = 1,NRN
      DO 4996 I = 1,IX
         XIX = NDEVS(NC,I)
         FXIX = XIX / INT(AMEAN)
         CNSR(NC,I,ND) = FXIX * CSR(NOCT,ND)
         CNGR(NC,I,ND) = FXIX * CGR(NOCT,ND)
         CNRR(NC,I,ND) = FXIX * CRR(NOCT,ND)
 4996 CONTINUE
 4997 CONTINUE
 5004 GO TO 3000
C
C***** CC: 000 ***********************************************************
C                                                                       *
C***** BRANCH 117                                                       *
C***** NORMAL GROUNDWATER FLOW - SALT MEDIA (117)                        *
C                                                                       *
C***** CC: 000 ***********************************************************
C
  117 XXG    = XHGH / XLOW
      CEE    =  K1(NC) * XXG * AREA(NC)
      CFF    =  KPRIM(NC) * XXG * AREA(NC)
      VOLSH = CEE + CFF * TCLOS
      IF (VOLSH .LE. VMIN) GO TO 591
      DVV    = (VTANK(NC) - VMIN) / TCLOS
      DA     = CFF / 2.0
      DB     = CEE + DVV
      DC     = - VTANK(NC)
      TRCH   = ROOT (DA,DB,DC)
C
      VRCH   = VTANK(NC) - DVV * TRCH
      DEE    = CEE * XILTH / XXG
      DFF    = CFF * XILTH / XXG
      DA     = DFF / 2.0
      DB     = DEE + DFF * TRCH
      DC     = - (VRCH - VMIN)
      TVMIN  = ROOT (DA,DB,DC)
      TRR    = TVMIN + TRCH
C
      TLLMT  = TRCH
      IF (TRCH .LT. CLIFE) TLLMT = CLIFE
      IF (DEE + DFF * TLLMT .GT. DVV) GO TO 920
      IFLOW   = 1
      DA     = XILTH * KPRIM(NC) / (2.0 * PORS(NC))
      DB     = K1(NC) + KPRIM(NC) * TRCH
      DB     = DB * XILTH / PORS(NC)
      DC     = - XLOW
      TDEL1  = ROOT (DA,DB,DC)
      GO TO 921
  920 IFLOW = 2
      TRR = TCLOS
      TDEL1 = XLOW * PORS(NC) * AREA(NC) / DVV
C
  921 IF (TRR .LE. CLIFE) GO TO 592
      DO 4090 ND=1,NRN
C
      CA     = LR(ND) * CLIFE
      WLRDT  = LR(ND) * EEXP (CA,IEX)
      CB     = LR(ND) * (TLLMT - CLIFE)
      CGB    = EEXP (-CB,IEX)
C
      QINT = 0.0
      TDEL2  = RNDA(ND) * WTIME
      TDEL   = TDEL1 + TDEL2
      TOUT   = TLLMT + TDEL
      IF (TOUT .GE. TB) GO TO 4090
      IF (TOUT*RNLDX(ND) .GE.  20.0) GO TO 4090
C
      CA = RNLDX(ND) * TDEL
      DECAYD = EEXP (-CA,IEX)
      ITRIG  = 0
C
      TMAX   = TB - TDEL
      IF (TRR .LT. TMAX) TMAX = TRR
      DELT    = 1.00
      IT     = (TLLMT + DELT) / DELT
      IMAX   = TMAX / DELT
C
      DO 4091 I=IT,IMAX
C
      FI = I
      T  = FI * DELT
C
      IF (I .EQ. IMAX) T = TMAX
      IF (ITRIG .EQ. 1) GO TO 911
      CINTOA = CINTA (TLLMT,DEE,DFF,VRCH,TRCH,LR(ND),DVV,IFLOW,IEX,
     1                VTANK(NC))
      TOLDA  = TLLMT
      AREAX   = 0.0
C
  911 THALF  = (T + TOLDA) / 2.0
      CA     = (T - TOLDA) / 6.0
      CINTH  = CINTA (THALF,DEE,DFF,VRCH,TRCH,LR(ND),DVV,IFLOW,IEX,
     2                VTANK(NC))
      CINTN  = CINTA (T,DEE,DFF,VRCH,TRCH,LR(ND),DVV,IFLOW,IEX,
     3                VTANK(NC))
      CB     = CINTOA + 4.0 * CINTH + CINTN
      CC     = CA * CB
      AREAX  = AREAX + CC
      TOLDA  = T
      CINTOA = CINTN
C
      CA     = RNLDX(ND) * T
      DECAY  = EEXP (-CA,IEX)
      CONC   = WLRDT * RNQOX(ND) * FTANK(NC) * DECAY * AREAX
      IF (TLLMT .EQ. CLIFE) GO TO 912
      CC     = (RNQOX(ND) * FTANK(NC) / VRCH) * DECAY * (1.0 - CGB)
      CONC   = CONC + CC
  912 IF (RNSOL(ND) .EQ. 0.0) GO TO 913
      IF (CONC .LT. RNSOL(ND)) GO TO 913
C
      IF (ITRIG .EQ. 1) GO TO 914
      TRNST  = TDEL + TLLMT
      GO TO 915
  914 TRNST  = TDEL + T - DELT
      GO TO 915
C
  913 IF (ITRIG .EQ. 1) GO TO 916
      QRTO   = 0.0
      TROLD  = TLLMT
C
  916 VOLF   = DEE + DFF * T
      IF (IFLOW .EQ. 2) VOLF = DVV
      QRTN   = VOLF * CONC * DECAYD
      CC     = 0.5 * (QRTN + QRTO) * (T - TROLD)
      QINT = QINT + CC
      QRTO   = QRTN
      TROLD  = T
      ITRIG  = 1
 4091 CONTINUE
      GO TO 930
C
  915 CA     = RNSOL(ND) * DECAYD
      IF (IFLOW .EQ. 1) GO TO 917
      CB      = - DVV * TDEL * CA
      CC      = DVV * CA / 2.0
      GO TO 918
  917 CB     = (DEE - DFF * TDEL) * CA
      CC     = DFF * CA / 2.0
  918 TULMT  = TRR + TDEL
      IF (TULMT .GT. TB) TULMT = TB
      CD     = CB * (TULMT - TRNST)
      CE     = CC * (TULMT**2.0 - TRNST**2.0)
      QINT = QINT + CD + CE
C
  930 CONS = QINT * (HFS1(ND) + HFS2(ND) / (LAMS(ND) + RNLDX(ND)))
      CONG = QINT * (HFG1(ND) + HFG2(ND) / (LAMS(ND) + RNLDX(ND)))
      CONR = QINT / RLMT(3,ND)
C
      IF (CONS .LE. CONSM) GO TO 931
      CONSM = CONS
      NRSMX(NC,1) = ND
  931 IF (CONG .LE. CONGM) GO TO 932
      NRGMX(NC,1) = ND
      CONGM = CONG
  932 IF (CONR .LE. CONRM) GO TO 933
      CONRM = CONR
      NRRMX(NC,1) = ND
  933 CONST = CONST + CONS
      CONGT = CONGT + CONG
      CONRT = CONRT + CONR
C
      CNSR(NC,1,ND) = CONS
      CNGR(NC,1,ND) = CONG
      CNRR(NC,1,ND) = CONR
C
 4090 CONTINUE
C
      CNS(NC,1) = CONST
      CNG(NC,1) = CONGT
      CNR(NC,1) = CONRT
C
      GO TO 3000
C
  591 ISALT = 1
      GO TO 593
  592 ISALT = 2
  593 CNS(NC,1) = 0.0
      CNG(NC,1) = 0.0
      CNR(NC,1) = 0.0
C
 3000 CONTINUE
      DO 7024 ND=1,NRN
      DO 7024 NC=1,NEVSM
      DO 7024 NB=1,NEVTM
      RIS=PROB(NC,NB)*CNSR(NC,NB,ND)
 7024 CONTINUE
C
C
C***** CC: 000 ***********************************************************
C                                                                        *
C***** RISKS CALCULATED                                                  *
C                                                                        *
C***** CC: 000 ***********************************************************
C
      DO 6100 NC=1,NEVSM
      RISKS(NC) = 0.0
      RISKG(NC) = 0.0
 6100 RISKR(NC) = 0.0
C
      DO 6103 ND=1,NRNM
      RRISKS(ND) = 0.0
      RRISKG(ND) = 0.0
 6103 RRISKR(ND) = 0.0
C
      IRRSK     = 0
C
```

```
      TRISKS    = 0.0
      TRISKG    = 0.0
      TRISKR    = 0.0
C
      DO 6101 NC=1,NEVSM
      DO 6102 NB=1,NEVTM
      RISKS(NC) = PROB(NC,NB) * CNS(NC,NB) + RISKS(NC)
      RISKG(NC) = PROB(NC,NB) * CNG(NC,NB) + RISKG(NC)
      RISKR(NC) = PROB(NC,NB) * CNR(NC,NB) + RISKR(NC)
      DO 6102 ND=1,NRNM
      RRISKS(ND) = PROB(NC,NB) * CNSR(NC,NB,ND) + RRISKS(ND)
      RRISKG(ND) = PROB(NC,NB) * CNGR(NC,NB,ND) + RRISKG(ND)
 6102 RRISKR(ND) = PROB(NC,NB) * CNRR(NC,NB,ND) + RRISKR(ND)
      TRISKS    = RISKS(NC) + TRISKS
      TRISKG    = RISKG(NC) + TRISKG
 6101 TRISKR    = RISKR(NC) + TRISKR
C
C***** CC: 000 *********************************************************
C                                                                      *
C***** PRINTOUTS - REMAINDER OF MAIN IS FORMAT AND WRITE STATEMENTS   *
C                                                                      *
C***** CC: 000 *********************************************************
C
      IF (NMAT .EQ. 1) GO TO 250
      WRITE (6,72)
   72 FORMAT (1H1)
      WRITE (6,30) (DASH(I),I=1,33)
   30 FORMAT (1H ,33A4/1H )
      WRITE (6,31) (TITLE(I),I=1,20)
      WRITE (6,31) (TITLE(I),I=21,40)
   31 FORMAT (1H ,26X,20A4)
      WRITE (6,32) (DASH(I),I=1,33)
   32 FORMAT (1H /1H ,33A4)
C
      WRITE (6,70) TRISKS,TRISKG
   70 FORMAT (1H ,'*****',4X,'THE (P)(C) RISK FOR THIS DOSE',
     1         ' COMMITMENT PERIOD IS',1PE9.2,' FOR SOMATIC',
     2         ' EFFECTS, AND',1PE9.2,' FOR GENETIC EFFECTS',
     3         5X,'*****')
      WRITE (6,71) (DASH(I),I=1,33)
   71 FORMAT (1H ,33A4)
      WRITE (6,74)
   74 FORMAT (1H ,'*****',4X,'THE (P)(C) RISK BY EVENT IS:',90X,'*****')
      DO 6110 I=1,NEVS
 6110 WRITE (6,75) EVNT(I),(EDES(I,L),L=1,4),RISKS(I),RISKG(I)
   75 FORMAT (1H ,'*****',23X,'EVENT',F6.1,2X,4A4,2X,1PE9.2,
     1         ' FOR SOMATIC EFFECTS',5X,1PE9.2,' FOR GENETIC EFFECTS',
     2         5X,'*****')
      WRITE (6,71) (DASH(I),I=1,33)
      WRITE (6,76)
   76 FORMAT (1H ,'*****',4X,'THE (P)(C) RISK BY RADIONUCLIDE IS:',83X,
     1              '*****')
      DO 6120 I=1,NRN
      IF (RRISKS(I) .NE. 0.0) GO TO 610
      IRRSK  =  1
      GO TO 6120
  610 WRITE (6,77) RNDS1(I),RNDS2(I),RRISKS(I),RRISKG(I)
   77 FORMAT (1H ,'*****',42X,2A4,4X,1PE9.2,' FOR SOMATIC EFFECTS',5X,
     1              1PE9.2,' FOR GENETIC EFFECTS',5X,'*****')
 6120 CONTINUE
      IF (IRRSK .EQ. 1) WRITE (6,78)
   78 FORMAT (1H ,'*****',43X,'CONTRIBUTION FROM ALL OTHER ',
     1              'RADIONUCLIDES WAS ZERO',29X,'*****')
      WRITE (6,71) (DASH(I),I=1,33)
C
      DO 6001 K=1,NEVS
      IF (NEVTT(K) .NE. 3) GO TO 651
 6001 CONTINUE
      GO TO 851
C
C
  651 DO 6000 I=NPA,NPB,NPC
C
      IF (I .EQ. 3 .OR. I .NE. NPA) GO TO 652
      WRITE (6,33)
   33 FORMAT (1H )
      WRITE (6,34)
   34 FORMAT (1H ,'EACH ENTRY IN THE FOLLOWING TABLES REPRESENTS THE ',
     1              'FOLLOWING DATA:'//
     21H ,5X,       '1.  THE TOTAL NUMBER OF HEALTH EFFECTS FROM ONE ',
     3              'SUCH EVENT INCURRED IN THIS DOSE COMMITMENT PERIOD.'/
     41H ,5X,       '2.  THE RADIONUCLIDE CONTRIBUTING THE MOST HEALTH ',
     5              'EFFECTS WITHIN THIS TOTAL.'/
     61H ,5X,       '3.  THE PROBABILITY OF AT LEAST ONE EVENT OF THIS ',
     7              'TYPE OCCURRING WITHIN THE TIME PERIOD REPRESENTED ',
     8              'BY THIS EVENT TIME')
      WRITE (6,33)
      GO TO 160
C
  652 IF (IRLMT .EQ. 1) GO TO 653
      WRITE (6,33)
      WRITE (6,39)
   39 FORMAT (1H ,'EACH ENTRY IN THE FOLLOWING TABLES REPRESENTS THE ',
     1              'FOLLOWING DATA:'//
     21H ,5X,       '1.  THE TOTAL RELEASE RATIO FROM ONE ',
     3              'SUCH EVENT INCURRED IN THIS DOSE COMMITMENT PERIOD.'/
     41H ,5X,       '2.  THE RADIONUCLIDE CONTRIBUTING THE LARGEST PART ',
     5              'OF THIS RELEASE RATIO.'/
     61H ,5X,       '3.  THE PROBABILITY OF AT LEAST ONE EVENT OF THIS ',
     7              'TYPE OCCURRING WITHIN THE TIME PERIOD REPRESENTED ',
     8              'BY THIS EVENT TIME')
```

```
      WRITE (6,33)
      GO TO 160
C
  653 WRITE (6,33)
      WRITE (6,42)
   42 FORMAT (1H ,'EACH ENTRY IN THE FOLLOWING TABLES REPRESENTS THE ',
     1             'FOLLOWING DATA:'//
     21H ,5X,      '1.  THE TOTAL NUMBER OF CURIES RELEASED FROM ONE ',
     3             'SUCH EVENT INCURRED IN THIS DOSE COMMITMENT PERIOD.'/
     41H ,5X,      '2.  THE RADIONUCLIDE CONTRIBUTING THE MOST ',
     5             'CURIES WITHIN THIS TOTAL.'/
     61H ,5X,      '3.  THE PROBABILITY OF AT LEAST ONE EVENT OF THIS ',
     7             'TYPE OCCURRING WITHIN THE TIME PERIOD REPRESENTED ',
     8             'BY THIS EVENT TIME')
      WRITE (6,33)
C
  160 IF (I .NE. 1) GO TO 161
      DO 6061 J=1,6
 6061 HELAB(J) = SOMLAB(J)
      GO TO 165
  161 IF (I .NE. 2) GO TO 162
      DO 6062 J=1,6
 6062 HELAB(J) = GENLAB(J)
      GO TO 165
  162 IF (IRLMT .EQ. 1) GO TO 163
      DO 6063 J=1,6
 6063 HELAB(J) = RROLAB(J)
      GO TO 165
  163 DO 6064 J=1,6
 6064 HELAB(J) = CURLAB(J)
  165 NSA = 1
C
      DO 7000 J=1,NPRT
C
      WRITE (6,30) (DASH(L),L=1,33)
      WRITE (6,35) NTA,NTB,(HELAB(L),L=1,6)
   35 FORMAT (1H ,3X,'DOSE COMMITMENT PERIOD = ',I7,' YEARS TO ',I7,
     1              ' YEARS',47X,6A4)
      WRITE (6,36)
   36 FORMAT (1H /1H ,60X,'EVENT TIMES'/1H )
C
      NFC = NOUT(J)
      NFCC = 2 * NFC
      NFA = NOUT(J) - 3
      IF (NFA .LT. 1) NFA = 1
      NSB = NSA + NFC - 1
      FMTA(4) = HFA(NFA)
      WRITE (6,FMTA) (NENTT(L),L=NSA,NSB)
      WRITE (6,41) (STARS(L),L=1,29)
   41 FORMAT (17X,29A4/1H ,16X,'*')
      FMTC(7) = HFC(NFA)
C
```

```
      IF (TEVNT(NSB) .GT. TEDC(NA)) GO TO 170
C
      FMTB(5) = HFB(NFC,NFA)
      FMTB(8) = BLANKS
      FMTB(9) = BLANKS
      FMTB(10)= BLANKS
C
      DO 8000 K=1,NEVS
C
      IF (NEVTT(K) .EQ. 3) GO TO 8000
      IF (I .NE. 1) GO TO 175
      WRITE (6,FMTB) (EVENT(L),L=1,4),(CNS(K,L),L=NSA,NSB)
      DO 8001 M=1,NFC
      NRA = NRSMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 172
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8001
  172 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8001 CONTINUE
      GO TO 176
  175 IF (I .NE. 2) GO TO 174
      WRITE (6,FMTB) (EVENT(L),L=1,4),(CNG(K,L),L=NSA,NSB)
      DO 8002 M=1,NFC
      NRA = NRGMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 173
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8002
  173 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8002 CONTINUE
      GO TO 176
  174 WRITE (6,FMTB) (EVENT(L),L=1,4),(CNR(K,L),L=NSA,NSB)
      DO 8006 M=1,NFC
      NRA = NRRMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 171
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8006
  171 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8006 CONTINUE
  176 WRITE (6,FMTC) EVNT(K),(RT(L),L=1,NFCC)
      WRITE (6,FMTB) (EDES(K,L),L=1,4),(PROB(K,L),L=NSA,NSB)
      WRITE (6,37)
   37 FORMAT (1H ,16X,'*')
 8000 CONTINUE
      WRITE (6,71) (DASH(L),L=1,33)
      NSA = NSB +1
      IF (TEVNT(NSA) .GT. TEDC(NA)) GO TO 6000
      GO TO 7000
C
  170 FMTB(8)  = AFORMA
      FMTB(10) = AFORMB
      DO 8003 L=NSA,NSB
      IF (TEVNT(L) .LE. TEDC(NA)) GO TO 8003
      NFD = L - NSA
      IF (NFD .LT. 1) NFD = 1
      NFE = NFD + 1
      NFF = NFC - NFD
      FMTB(5) = HFB(NFD,NFA)
      FMTB(9) = HFB(NFF,NFA)
      DO 8005 K=NFE,NFC
      RT(2*K-1) = DASH(1)
 8005 RT(2*K)   = DASH(1)
      GO TO 177
 8003 CONTINUE
C
  177 DO 8100 K=1,NEVS
C
      IF (NEVTT(K) .EQ. 3) GO TO 8100
      IP = 1
      DO 8201 M=NSA,NSB
      PROBT(IP) = PROB(K,M)
 8201 IP = IP + 1
      DO 8202 M=NFE,NFC
 8202 PROBT(M) = DDASH
C
      IF (I .NE. 1) GO TO 178
      IP = 1
      DO 8203 M=NSA,NSB
      CNT(IP) = CNS(K,M)
 8203 IP = IP + 1
      DO 8204 M=NFE,NFC
 8204 CNT(M) = DDASH
      WRITE (6,FMTB) (EVENT(L),L=1,4),(CNT(L),L=1,NFC)
      DO 8102 M=1,NFD
      NRA = NRSMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 179
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8102
  179 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8102 CONTINUE
      GO TO 180
  178 IF (I .NE. 2) GO TO 182
      IP = 1
      DO 8205 M=NSA,NSB
      CNT(IP) = CNG(K,M)
 8205 IP = IP + 1
      DO 8206 M=NFE,NFC
 8206 CNT(M) = DDASH
      WRITE (6,FMTB) (EVENT(L),L=1,4),(CNT(L),L=1,NFC)
      DO 8103 M=1,NFD
      NRA = NRGMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 181
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8103
  181 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8103 CONTINUE
      GO TO 180
  182 IP = 1
      DO 8207 M=NSA,NSB
      CNT(IP) = CNR(K,M)
 8207 IP = IP + 1
      DO 8208 M=NFE,NFC
 8208 CNT(M) = DDASH
      WRITE (6,FMTB) (EVENT(L),L=1,4),(CNT(L),L=1,NFC)
      DO 8104 M=1,NFD
      NRA = NRRMX(K,NSA+M-1)
      IF (NRA .LE. 0) GO TO 183
      RT(2*M-1) = RNDS1(NRA)
      RT(2*M)   = RNDS2(NRA)
      GO TO 8104
  183 RT(2*M-1) = BLANKS
      RT(2*M)   = BLANKS
 8104 CONTINUE
  180 WRITE (6,FMTC) EVNT(K),(RT(L),L=1,NFCC)
      WRITE (6,FMTB) (EDES(K,L),L=1,4),(PROBT(L),L=1,NFC)
      WRITE (6,37)
 8100 CONTINUE
      WRITE (6,71) (DASH(L),L=1,33)
      GO TO 6000
 7000 CONTINUE
C
 6000 CONTINUE
C
      DO 8501 K=1,NEVS
      IF (NEVTT(K) .EQ. 3) GO TO 851
 8501 CONTINUE
      GO TO 259
C
  851 WRITE (6,71) (DASH(I),I=1,33)
      WRITE (6,81) NTIC,NTE
```

```
   81 FORMAT (1H /1H ,'FOR RELATIVELY LIKELY HUMAN INTRUSION EVENTS, ',
     1        'MULTIPLE OCCURRENCES ARE ASSUMED.  THE EVENT TIMES FOR ',
     2        'EACH OCCURRENCE ARE EVENLY'/
     3 1H ,   'SPACED THROUGHOUT THE PERIOD FROM LOSS OF INSTITUTIONAL ',
     4        'CONTROLS (',I5,' YEARS) TO THE END OF THE EVENT ',
     5        'PERIOD (',I6,' YEARS).'/
     6 1H ,   'FOR EACH CASE, THE CONSEQUENCES ARE SUMMED OVER ',
     7        'THESE MULTIPLE OCCURRENCES.'/1H )
      WRITE (6,71) (DASH(I),I=1,33)
      DO 8500 K=1,NEVS
C
      IF (NEVTT(K) .NE. 3) GO TO 8500
      NDCS = NDCASE(K)
      WRITE (6,82) NDCS,EVNT(K),NTIC,(EDES(K,L),L=1,4),NTE
   82 FORMAT (1H /1H ,5X,'EVENT',15X,I2,' CASES WERE RUN FOR ',
     1        'DIFFERENT EXPECTED NUMBERS OF OCCURRENCES.'/
     2 1H ,    4X,F5.1,16X,'FROM',I6,' YEARS'/
     3 1H ,    4A4,9X,'TO  ',I6,' YEARS'/1H )
      IF (IRLMT .NE. 1) WRITE (6,83)
   83 FORMAT (1H ,21X,'NUMBER OF',9X,'PROBABILITY OF',
     1         12X,'SOMATIC',16X,'GENETIC'/
     2 1H ,    20X,'OCCURRENCES',10X,'THIS NUMBER',
     3         1X,2(9X,'HEALTH EFFECTS'),9X,'RELEASE RATIOS')
      IF (IRLMT .EQ. 1) WRITE (6,85)
   85 FORMAT (1H ,21X,'NUMBER OF',9X,'PROBABILITY OF',
     1         12X,'SOMATIC',16X,'GENETIC'/
     2 1H ,    20X,'OCCURRENCES',10X,'THIS NUMBER',
     3         1X,2(9X,'HEALTH EFFECTS'),8X,'CURIES RELEASED')
      WRITE (6,33)
C
      DO 8510 I=1,NDCS
 8510 WRITE (6,84) NDEVS(K,I),PROB(K,I),CNS(K,I),CNG(K,I),CNR(K,I)
   84 FORMAT (1H ,23X,I3,15X,1PE9.2,3(14X,1PE9.2))
      WRITE (6,32) (DASH(I),I=1,33)
C
 8500 CONTINUE
C
C*α*α
C     WRITE (6,72)
C     WRITE (6,61) ((I,J,PROB(I,J),CNS(I,J),J=1,NEVT),I=1,NEVS)
C     WRITE (6,63)
C     WRITE (6,61) ((I,J,PROB(I,J),CNG(I,J),J=1,NEVT),I=1,NEVS)
C  61 FORMAT (4(1H ,2I3,1P2E9.2))
C  63 FORMAT (1H )
C*α*α
C
  250 IF (NMAT .NE. 1) GO TO 259
      IF (NA .EQ. 1) WRITE (6,72)
      WRITE (6,32) (DASH(I),I=1,33)
      WRITE (6,64) NTA,NTB
   64 FORMAT (1H ,4X,'THE (P)(C) RISK FOR THE DOSE COMMITMENT PERIOD ',
     1          I7,' YEARS TO ',I7,' YEARS IS:')
      DO 6010 I=NPA,NPB,NPC
      IF (I .EQ. 1) WRITE (6,65) TRISKS,(SOMLAB(L),L=1,6)
      IF (I .EQ. 2) WRITE (6,65) TRISKG,(GENLAB(L),L=1,6)
      IF (I .EQ. 3 .AND. IRLMT .NE. 1)
     1             WRITE (6,65) TRISKR,(RROLAB(L),L=1,6)
      IF (I .EQ. 3 .AND. IRLMT .EQ. 1)
     1             WRITE (6,65) TRISKR,(CURLAB(L),L=1,6)
   65 FORMAT (1H ,99X,1PE9.2,' FOR',6A4)
 6010 CONTINUE
      WRITE (6,32) (DASH(I),I=1,33)
C
  259 IF (NTS .EQ. 1)
     1 CALL PCPLOT (PROB,CNS,NCT,NEVS,NEVT,NEVSM,NEVTM,NPCA,NPCP,X,Y)
      IF (NTG .EQ. 1)
     1 CALL PCPLOT (PROB,CNG,NCT,NEVS,NEVT,NEVSM,NEVTM,NPCA,NPCP,X,Y)
      IF (NTR .EQ. 1)
     1 CALL PCPLOT (PROB,CNR,NCT,NEVS,NEVT,NEVSM,NEVTM,NPCA,NPCP,X,Y)
C
      IF (IEX .EQ. 1) WRITE (6,73)
   73 FORMAT (1H1,10X,'CAUTION: AN OVERFLOW CONDITION HAS OCCURRED IN ',
     1               'FUNCTION EEXP IN THIS TIME PERIOD.')
C
 1000 CONTINUE
C
      IF (NDOO .EQ. 1 .OR. NDOT .EQ. 1) GO TO 360
      NDOT = 1
      GO TO 350
C
  360 WRITE (6,50)
   50 FORMAT (1H //1H ,9X,'PROBLEM COMPLETED')
C
      IF (N1 .NE. 96) GO TO 371
C
      WRITE (6,21)
      DO 3012 I=1,NEVSM
 3012 EVNT(I) = 0.0
      NEVS    = 0
      DO 1235 I=1,NEVTM
      DO 1235 J=1,NEVSM
      FRATE(J,I) = 0.0
 1235 PROB (J,I) = 0.0
      GO TO 555
C
  371 IF (N1 .NE. 97) GO TO 372
C
      WRITE (6,21)
      DO 4004 I=1,NRNM
      RNLD(I)  = 0.0
      RNLD1(I) = 0.0
      RNLDX(I) = 0.0
      RNQU1(I) = 0.0
      RNQOX(I) = 0.0
 4004 RNID(I)  = 0.0
      NRN      = 0
      IPATH    = 0
      IRLMT    = 1
      GO TO 555
C
  372 IF (N1 .NE. 98) GO TO 370
      WRITE (6,21)
      GO TO 555
C
  370 STOP 1000
      END
C
```

```
C***** CC: 000 *****************************************************************
C                                                                             *
C***** FUNCTIONS AND SUBROUTINES                                              *
C                                                                             *
C******************************************************************************
C
      SUBROUTINE SMESS1
     1       (RNLD,LAMG,LAMS,LAMR,TEV,T,MESS1N,MESSA,IEX)
C
      REAL*4 LAMG,LAMS,LAMR,MESS1N,MESSA,M5N,M6N
C
      A5N = - (RNLD + LAMG)
      B6N = - (RNLD + LAMS + LAMR)
      B4N = - (A5N + B6N)
      C4N = A5N * B6N - LAMG * LAMR
C
      CA = (B4N**2 - 4.0 * C4N)**0.5
C
      M5N = (- B4N + CA) / 2.0
      M6N = (- B4N - CA) / 2.0
C
      CB  = M6N - A5N
      CC  = M6N - M5N
      CD  = A5N - M5N
      CE  = M5N * (T - TEV)
      CF  = M6N * (T - TEV)
C
      CE  = EEXP (CE,IEX) - 1.0
      CF  = EEXP (CF,IEX) - 1.0
C
      CG  = CB * CE / (M5N * CC)
      CH  = CD * CF / (M6N * CC)
C
      MESS1N = CG + CH
C
      CI  = - CD * CB / (LAMR * CC)
      CJ  = CE / M5N - CF / M6N
C
      MESSA = CI * CJ
C
      RETURN
      END
      FUNCTION CINTA (S,DA,DB,VRCH,TRCH,WLR,DVV,I,IEX,VR)
C
      GO TO (10,20), I
C
   10 DK = VRCH + DA * TRCH + DB * TRCH**2.0 / 2.0
      DC = WLR * S
      DC = EEXP (-DC,IEX)
C
      DD = DK - DA * S - DB * S**2.0 / 2.0
C
      GO TO 30
   20 DK       = VR
      DC       = WLR * S
      DC       = EEXP(-DC,IEX)
C
      DD       = DK - DVV * S
C
   30 CINTA = DC / DD
C
      RETURN
      END
      FUNCTION SMESSN (RNLD,LR,SF1,SF2,TAU1,TAU2,TDEL,T,IEX)
C
      REAL*4 M1N,M2N
      REAL LR
C
      A1N = - (RNLD + SF1 + TAU1)
      B2N = - (RNLD + SF2 + TAU2)
      WN  = - (RNLD + LR)
      B3N = - (A1N + B2N)
      C3N = A1N * B2N - (TAU1 * TAU2 + TAU2 * SF1)
C
      CA  = (B3N**2 - 4.0 * C3N)**0.5
C
      M1N = (- B3N + CA) / 2.0
      M2N = (- B3N - CA) / 2.0
C
      CB  = M1N * (T - TDEL)
      CC  = M2N * (T - TDEL)
      CD  = WN  * (T - TDEL)
C
      CB  = EEXP (CB,IEX) - 1.0
      CC  = EEXP (CC,IEX) - 1.0
      CD  = EEXP (CD,IEX) - 1.0
C
      CE  = (A1N - M2N) * CB / ((WN - M1N) * M1N)
      CF  = (A1N - M1N) * CC / ((WN - M2N) * M2N)
      CG  = (M2N - M1N) * (WN - B2N) * CD /
     1       ((WN - M2N) * (WN - M1N) * WN)
C
      SMESSN = (CE - CF + CG) / (M2N - M1N)
C
      RETURN
      END




      FUNCTION QINTT (RNLD,LR,TDEL,T,IEX)
      REAL LR
C
      CA = - RNLD * TDEL
      CB = - (RNLD + LR) * T + LR * TDEL
C
      QINTT = EEXP (CA,IEX) - EEXP (CB,IEX)
C
      RETURN
      END
      SUBROUTINE PCPLOT (P,C,NCT,NEVS,NEVT,NSM,NTM,NA,NP,X,Y)
C
      DIMENSION X(NCT),Y(NCT),P(NSM,NTM),C(NSM,NTM)
C
      REAL*8 X,Y,P,C,XSAVE1,XSAVE2,YSAVE1,YSAVE2
C
      DATA IUNIT/10/
C
      DO 1100 I=1,NCT
      X(I) = 0.0
 1100 Y(I) = 0.0
      NNUM = 0
C
      DO 1500 I=1,NEVS
      DO 1000 L=1,NEVT
C
      IF (P(I,L) .LE. 0.0) GO TO 1000
      IF (C(I,L) .LE. 0.0) GO TO 1000
C
      ITRIG = 0
      NNUM = NNUM + 1
C
      DO 2000 J=1,NCT
C
      IF (ITRIG .EQ. 1) GO TO 100
      IF (C(I,L) .LT. X(J)) GO TO 2000
C
      XSAVE1 = X(J)
      YSAVE1 = Y(J)
      X(J) = C(I,L)
      IF (J .EQ. 1) GO TO 101
      Y(J) = Y(J-1) + P(I,L)
      IF (XSAVE1 .EQ. 0.0) GO TO 1000
      ITRIG = 1
      GO TO 2000
  101 Y(J) = P(I,L)
      IF (XSAVE1 .EQ. 0.0) GO TO 1000
      ITRIG = 1
      GO TO 2000
C
  100 XSAVE2 = X(J)
      YSAVE2 = Y(J)
      X(J) = XSAVE1
      Y(J) = YSAVE1 + P(I,L)
      IF (XSAVE2 .EQ. 0.0) GO TO 1000
      XSAVE1 = XSAVE2
      YSAVE1 = YSAVE2
C
 2000 CONTINUE
 1000 CONTINUE
 1500 CONTINUE
C
```

```
      DO 3000 I=1,NNUM
      IF (Y(I) .LT. 0.04) GO TO 3000
      Y(I) = 1.0 - DEXP (-Y(I))
 3000 CONTINUE
C
C*α*
      IF (NA .EQ. 1) GO TO 200
      WRITE (6,10) NNUM,NCT,NEVS,NEVT
   10 FORMAT (1H /1H ,10X,4I6)
      WRITE (6,12)
C     WRITE (6,13) ((I,J,P(I,J),C(I,J),J=1,NEVT),I=1,NEVS)
C  13 FORMAT (4(1H ,2I3,1P2E9.2))
   11 FORMAT (1H ,1P14E9.2)
      WRITE (6,12)
      WRITE (6,11) (Y(I),X(I),I=1,NNUM)
   12 FORMAT (1H )
C*α*
C
  200 IF (NP .EQ. 1) GO TO 300
      DO 4000 I=1,NNUM
 4000 WRITE (IUNIT) Y(I),X(I)
      REWIND IUNIT
      IUNIT = IUNIT + 1
C
  300 RETURN
      END
      SUBROUTINE ERROR (IN,NA,NB,F,A,IX)
C
      DIMENSION F(6),A(4)
C
      IF (IN .GT. 5) GO TO 100
C
      WRITE (6,10) IN,NA,NB,(F(I),I=1,6),(A(I),I=1,4)
   10 FORMAT (1H ,'ERROR ',I2,10X,I2,2X,I2,6(2X,1PE10.2),2X,4A4)
      WRITE (6,11)
   11 FORMAT (1H ,10X,'THE ABOVE INPUT CARD IS INCORRECT')
      IF (IX .NE. 1) IX = 1
      RETURN
C
  100 WRITE (6,10) IN,NA,NB,(F(I),I=1,6),(A(I),I=1,4)
      STOP 1002
      END
```

```
      FUNCTION BINOM (TB,R,P)
C
      IF (R .EQ. 0.0) GO TO 300
C
      Y = TB / R
      X = (1 - P)**Y
      Z = 1.0
      JR = R
C
      DO 100 I=1,JR
      Z = (TB + 1 - I) * Z * P * X / ((R + 1 - I) * (1 - P))
  100 CONTINUE
      GO TO 200
C
  300 Z = (1 - P)**TB
C
  200 BINOM = Z
C
      RETURN
      END
      FUNCTION EQUAL (VY,VAQ,NT,TMAX,TMIN,IEX)
C
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      IMIN = TMIN
      IF (IMIN .EQ. 0) IMIN = 1
      IMAX = TMAX
      TIME = -1.0
C
      DO 100 I=IMIN,IMAX,NT
      TI = I
      VT = VOLFLO(IEX,TI)
      VT = VY * VT
      IF (VT .GT. VAQ) GO TO 100
      TIME = I
      GO TO 200
  100 CONTINUE
C
      IF (TIME .EQ. -1.0) TIME = TMAX
C
  200 EQUAL = TIME
C
      RETURN
      END
      FUNCTION ENT1A (TF,TI,VAQ,CL,LR,VR,TEVNT,RNLD,RNQO,IEX)
C
      REAL LR
C
      AL1 = (VAQ / VR) - LR
      AL2 = RNLD + VAQ / VR
      A1 = LR * CL
      A1 = EEXP (A1,IEX)
      A1 = A1 * RNQO / VR
      E1 = A1 * LR / AL1
      G1 = VAQ * TEVNT / VR
      G2 = -LR * CL
      G3 = AL1 * TEVNT
      P1 = AL2 - AL1
      P3 = E1  / P1
      Q1 = -TI * AL2
      Q2 = -TF * AL2
      R1 = - P1 * TF
      R2 = - P1 * TI
      P4 = P3 * VAQ
      P4 = ALOG (P4)
      P5 = E1 * VAQ / AL2
      P5 = ALOG (P5)
      P6 = A1 * VAQ / AL2
      P6 = ALOG (P6)
C
      S1 = P4 + R1
      S2 = P4 + R2
      S3 = Q2 + P5 + G3
      S4 = Q2 + P6 + G1 + G2
      S5 = Q2 + P6 + G3
      S6 = Q1 + P5 + G3
      S7 = Q1 + P6 + G1 + G2
      S8 = Q1 + P6 + G3
C
      S1 = EEXP (S1,IEX)
      S2 = EEXP (S2,IEX)
      S3 = EEXP (S3,IEX)
      S4 = EEXP (S4,IEX)
      S5 = EEXP (S5,IEX)
      S6 = EEXP (S6,IEX)
      S7 = EEXP (S7,IEX)
      S8 = EEXP (S8,IEX)
C
      ENT1A =- S1 + S2 + S3 - S4 + S5 - S6 + S7 - S8
C
      RETURN
      END
      FUNCTION ENTCO (VY,RNSOL,TF,TI,IEX)
C
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      VA = 0.0
      VB = 0.0
      DO 1 I = 1,NCOF
      AX = - ALPH(I) * TF
      BX = - ALPH(I) * TI
      VA = VA + EEXP(AX,IEX) * CVA(I) / ALPH(I)
      VB = VB + EEXP(BX,IEX) * CVA(I) / ALPH(I)
    1 CONTINUE
      F1 = VB - VA
      F2 = CVC * (TF - TI)
C
      ENTCO = (F1 + F2) * RNSOL * VY
C
      RETURN
      END


      FUNCTION ENTANK (AA,K1,KPRIM,RNLD,RNQO,VR,TF,TI,LR,CL,IEX,NN)
C
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      REAL KPRIM,K1,LR
C
      A1 = LR * CL
      C1 = RNQO / VR * (K1 - KPRIM * TI)
      C2 = EEXP (A1,IEX)
      C3 = RNQO * KPRIM / VR
      IF (LR .EQ. 0.0) C2 = 0.0
      GA1 = RNLD + LR
      X = 0.
      H = (TF - TI) / NN
C
      YN = FUNC(AA,C1,C2,C3,GA1,TF,RNLD,IEX)
      YO = FUNC(AA,C1,C2,C3,GA1,TI,RNLD,IEX)
C
      DO 100 I = 2,NN,2
      IF (I .EQ. NN) GO TO 200
      T = TI + I * H
      Z = FUNC(AA,C1,C2,C3,GA1,T,RNLD,IEX)
      X = X + 2. * Z
  200 T = TI + (I-1) * H
      Z = FUNC(AA,C1,C2,C3,GA1,T,RNLD,IEX)
      X = X + 4.* Z
  100 CONTINUE
C
      ENTANK = ( YO + YN + X ) * H /3.
C
      RETURN
      END
      FUNCTION FUNC (AA,C1,C2,C3,GA1,T,RNLD,IEX)
C
      F1 = C1 + C3 * T
      F2 = - RNLD * T
      F2 = EEXP(F2,IEX)
      F3 = - GA1 * T
      F3 = C2 * EEXP(F3,IEX)
      F4 = ( F2 - F3 ) * F1
      G1 = AA * VOLFLO(IEX,T)
      G3 = F4 * G1
C
      FUNC = G3
C
      RETURN
      END
```

```
      FUNCTION TANK (VR,LR,CL,T,RNQO,RNLD,IEX)
C
      REAL LR
C
      A = -LR * (T - CL)
      B = -RNLD * T
      A = EEXP (A,IEX)
      B = EEXP (B,IEX)
      C = (1.0 - A) * B
C
      TANK = (C * RNQO) / VR
C
      RETURN
      END
      FUNCTION TDELI (X,TS,POR,XK,IEX,TB)
C
      DIST   = 0.0
      T      = TS
      ITB    = TB
      DELT   = 1.0
C
      DO 1000 I=1,ITB
C
      CD = XK * VOLFLO(IEX,T)
C
      DDEL = (CD / POR) * DELT
      DIST = DIST + DDEL
C
      IF (DIST .GT. X) GO TO 100
      T    = T + DELT
C
 1000 CONTINUE
C
  100 TDELI = T - TS
C
      RETURN
      END



      FUNCTION TDELKI (X,TS,POR,XK1,XKPR,IEX,TB)
C
      DIST     = 0.0
      T        = TS
      ITB      = TB
      DELT     = 1.0
C
      DO 1000 I=1,ITB
C
      CA       = VOLFLO(IEX,T)
      CB       = XK1 * CA
      CE       = XKPR * T * CA
      CG       = CB + CE
C
      DDEL     = (CG / POR) * DELT
      DIST     = DIST + DDEL
C
      IF (DIST .GT. X) GO TO 100
      T        = T + DELT
 1000 CONTINUE
C
  100 TDELKI  = T - TS
C
      RETURN
      END
      FUNCTION EEXP (X,IX)
C
      IF (X .GT. -100.0) GO TO 10
      EEXP    = 0.0
      RETURN
C
   10 IF (X .LT. 172.00) GO TO 20
      EEXP    = 4.0E75
      IX      = 1
      RETURN
C
   20 EEXP    = EXP (X)
      RETURN
      END
```

```
      FUNCTION DTANK (V,LR,CL,T,FR,RNQO,RNLD,RNQO1,RNLD1,IEX)
C
      REAL LR
C
      A = RNLD * RNQO * FR / V
      B = CL * LR
      CO = A / (RNLD - RNLD1)
      A1 = -RNLD1 * T
      A1 = EEXP (A1,IEX)
      B1 = -RNLD * T
      B1 = EEXP (B1,IEX) * CO
      C1 = RNQO1 * FR / V
      C3 = C1 + CO
      C2 = - LR * T
      C2 = EEXP(C2,IEX)
      B = EEXP(B,IEX)
C
      X = - C3 * A1 * B * C2 + ( CO + C1 * B ) * A1
C
      Y = B1 * ( B * C2 - 1. )
C
      DTANK = X + Y
C
      RETURN
      END
      FUNCTION TFAC3 (RNLD,LAMS,TEV,T,IEX)
C
      REAL*4 LAMS
C
      CA = RNLD + LAMS
      CB = - CA * (T - TEV)
      CB = EEXP (CB,IEX)
C
      TFAC3 = (1.0 - CB) / CA
C
      RETURN
      END
```

```
      FUNCTION TFAC4 (RNLD,LAMS,LAMR,TEV,T,IEX)
C
      REAL*4 LAMS,LAMR
C
      CA = RNLD + LAMS + LAMR
      CB = - CA * (T - TEV)
      CB = EEXP (CB,IEX)
C
      TFAC4 = LAMR * (1.0 - CB) / CA
C
      RETURN
      END
```

```
      FUNCTION TFAC5 (RNLD,LAMS,LAMR,TEV,T,IEX)
C
      REAL*4 LAMS,LAMR
C
      CA = RNLD + LAMS
      CB = - CA * (T - TEV)
      CB = EEXP (CB,IEX)
      CC = (1.0 - CB) / CA
C
      CD = RNLD + LAMS + LAMR
      CE = - CD * (T - TEV)
      CE = EEXP (CE,IEX)
      CF = (CE - 1.0) / CD
C
      TFAC5 = CC + CF
C
      RETURN
      END
      FUNCTION SALT(VY,LR,VR,TE,TI,TF,NN,IEX,CL,RNQO,RNLD,VAQ)
      INTEGER IER
      REAL LR,DCADRE,AF1,A,AERR,RERR,ERROR,C
      EXTERNAL AF1
      COMMON /BLOCK3/ VAR,VAY,P1,C1,D1,E1,F1,IEX1
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      VAR = VR
      VAY = VY
      IEX1 = IEX
      X=0.0
      CX = 0.0
      NL = NN + 1
      CC = VY * CVC
      P1=-LR+CC/VR
      A1=-LR*CL
      B1=-LR*TE
      E1=(LR*RNQO/VR)*EEXP(-A1,IEX)
      R1=(RNQO/VR)
      R1=ALOG(R1)
      W1 = VAQ / VR
      W2 = VAQ / VR -LR
      W3 = RNLD + VAQ / VR
      E2 = E1 / W2
      E2 = ALOG(E2)
      G1=-RNLD-CC/VR
      W4 = - G1 * TI
      W5 = E2 - W3 * TI
      W6 = W2 * TI
      W7 = W2 * TE
      W8 = R1 - A1 + W1 * TE - W3 * TI
      B2=EEXP(B1,IEX)
      A3=EEXP(A1,IEX)
      DO 2 I=1,NCOF
      AX = - ALPH(I) * TI
      CX = CX - CVA(I) * EEXP(AX,IEX) * VY / ( VR * ALPH(I))
    2 CONTINUE
      A4 = CX
      H3 = (TF - 110. - TI) / (NN - 20)
      H4 = 10.
      H2 = 1.
      DO 100 I = 1,NL
      T1 = I - 1
      IF (I .GT. 11) H2 = H4
      IF (I .GT. 11) T1 = 10. * (I - 11) + 10.
      IF (I .GT. 21) H2 = H3
      IF (I .GT. 21) T1 = 110. + H2 * (I - 21)
      T = T1 + TI
      XA=G1*T
      CX = 0.0
      DO 1 J=1,NCOF
      AX = - ALPH(J) * T
      CX = CX + CVA(J) * EEXP(AX,IEX) * VY / ( VR * ALPH(J))
    1 CONTINUE
      F1=XA+CX
      F2 = F1 + W5 + W6 + W4 + A4
      F2 = EEXP(F2,IEX)
      F3 = F1 + W5 + W7 + W4 + A4
      F3 = EEXP(F3,IEX)
      F4 = F1+ W8 + W4 + A4
      F4=EEXP(F4,IEX)
      H1=F4*(A3-B2)+F2-F3
      RERR = .095
      AERR = 0.0
      Y = DCADRE(AF1,TI,T,AERR,RERR,ERROR,IER)
      IF (IER .LT. 100) GO TO 200
  200 CT = Y + H1
      VT = VY * VOLFLO(IEX,T)
      FIX1 = CT * VT * H2
      IF (I .EQ. 1 .OR. I .EQ. NL) GO TO 101
      IF (I .EQ. 21) GO TO 300
      IF (I .EQ. 11) GO TO 400
      FIX1 = 4. * FIX1
      IF ((MOD(I,2)) .EQ. 0) GO TO 101
      FIX1 = FIX1 / 2.
      GO TO 101
  300 FIX1 = FIX1 * (10. + H3) / H2
      GO TO 101
  400 FIX1 = FIX1 * (1. + 10.) / H2
  101 CONTINUE
  100 X = X + FIX1
      IEX = IEX1
      SALT = X / 3.
      RETURN
      END
      FUNCTION AF1(S)
      REAL S
      COMMON /BLOCK3/ VAR,VAY,P1,C1,D1,E1,F1,IEX1
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      AX = 0.0
      DO 1 I = 1,NCOF
      BX = - ALPH(I) * S
      AX = AX - EEXP(BX,IEX1) * CVA(I) * VAY / ( VAR * ALPH(I))
    1 CONTINUE
      C1 = AX
      A1 = P1 * S + C1
      A2=ALOG(E1)
      A3=A1+A2+F1
      AF1  =  EEXP(A3,IEX1)
      RETURN
      END
```

```
      FUNCTION ROOT (A,B,C)
C
      IF (A .NE. 0.) GO TO 100
      ROOT = - C / B
  100 CA = B**2.0 - 4.0 * A * C
      CA = SQRT (CA)
      ROOT = (CA - B) / (2.0 * A)
      RETURN
      END
```

```
      FUNCTION VOLFLO(IEX,T)
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
C
      VX = 0.0
      DO 1 I= 1,NCOF
      AX = -ALPH(I) * T
      VX = VX + CVA(I) * EEXP(AX,IEX)
    1 CONTINUE
      VOLFLO = VX + CVC
      RETURN
      END
      FUNCTION VTSOL (TT,IEX,VAQ,RNSOL,RNLDX,RNQOX,VR,CLIFE,
     1                TFAIL,TVAQ,AREA,K1,LR)
C
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      REAL LR,K1
      X = VAQ * RNSOL / RNLDX
      Y = RNQOX
      A = RNLDX *TFAIL
      B = RNLDX * TVAQ
      A1 = X * EEXP(A,IEX) + Y
      Z = VR * RNSOL
      IF ( TFAIL .EQ. CLIFE ) Y = Y + VR * RNSOL * EEXP(RNLDX*CLIFE,IEX)
      IF(TFAIL .GE. TVAQ) ACTVAQ = Y * EEXP(-A,IEX) - VR * RNSOL
      X1 = AREA * K1 * RNSOL
      C = RNLDX * TT
      Y1 = CVC / RNLDX
C
      VX = 0.
      AX = 0.0
      BX = 0.0
C
      DO 100 I=1,NCOF
      VX = VX + CVA(I) * (EEXP(-ALPH(I) * TT,IEX))
      A4 = ALPH(I) - RNLDX
      AX = AX + CVA(I) * EEXP(-ALPH(I) * TVAQ,IEX) / A4
      BX = BX + CVA(I) * EEXP(-ALPH(I) * TT,IEX) / A4
  100 CONTINUE
      VX = ( VX + CVC ) * X1
      A = A1 * EEXP(-B,IEX) - X - AX * X1 + Y1 * X1
      IF ( TVAQ .LE. TFAIL ) A = Y * EEXP(-B,IEX) + X1 * Y1 - X1 * AX
      ACT = A * EEXP( B-C , IEX ) + X1 * BX - Z - X1 * Y1
      GT = RNLDX * RNSOL * VR + VX
      GT = GT / ACT
      IF (GT .GE. LR) VTSOL = TT
      IF (GT .LT. LR) VTSOL = -1.0
      RETURN
      END
```

```
      SUBROUTINE UERTST(IER,X)
      IF (IER .GT. 66) WRITE(6,100) IER
  100 FORMAT(1H ,'IER = ',I3,'(ANSWERS MAY NOT BE WITHIN THE SPECIFIED
     1ERROR RANGE DUE TO AN ILL BEHAVED FUNCTION)')
      RETURN
      END
      FUNCTION VQSOL(T1,IEX,VAQ,RNSOL,RNLDX,RNQOX,VR,CLIFE,
     1                 TFAIL,TVAQ,AREA,K1,LR)
      REAL LR,K1
      X =  RNSOL * (RNLDX * VR + VAQ)
      Y = RNQOX
      Z = EEXP(RNLDX * TFAIL,IEX) * VAQ * RNSOL / RNLDX
      U = EEXP(-RNLDX*T1,IEX)
      ACTVAQ = (Y + Z) * U - X / RNLDX
      FTVAQ = X / ACTVAQ
      IF (FTVAQ .GE. LR) GO TO 100
      VQSOL = -1.0
      RETURN
  100 VQSOL =T1
      RETURN
      END
```

```
      FUNCTION AF2(S)
      REAL S,LR,K1
      COMMON /BLOCK1/ E1,TAX,V,AREA(10),K1(10),RNLDX(20),NC,ND,Y1X,IEX
      X = ALOG(E1)
      Y = -XMU(TAX,IEX,V,AREA(NC),K1(NC),RNLDX(ND))
      Z = XMU(S,IEX,V,AREA(NC),K1(NC),RNLDX(ND))
      W = -Y1X * S
      VM = X + Y + Z + W
      AF2 = EEXP(VM,IEX)
      RETURN
      END
```

```
      FUNCTION XMU(T,IEX,VR,AREA,K1,RNLDX)
      COMMON /BLOCK2/ CVA(10),ALPH(10),CVC,NCOF
      REAL K1
      VA = 0.0
      DO 100 I = 1,NCOF
      VA = VA - CVA(I) * EEXP(-ALPH(I) * T , IEX ) / (ALPH(I) * VR)
  100 CONTINUE
      VA = (VA + T * CVC / VR ) * AREA * K1 + RNLDX *T
      XMU = VA
      RETURN
      END
      FUNCTION CONVT(TA,VAQ,RNSOL,XRNLDX,RNQOX,XVR,CLIFE,
     1                 TFAIL,TVAQ,XAREA,XK1,LR)
      INTEGER IER
      REAL LR,DCADRE,AF2,A,AERR,RERR,ERROR,C,K1
      EXTERNAL AF2
      COMMON /BLOCK1/ E1,TAX,V,AREA(10),K1(10),RNLDX(20),NC,ND,Y1X,IEX
      TT = TA
      TAX = TT
      Y1X = LR + XRNLDX
      A1 = -LR * CLIFE
      B1 = -LR * TFAIL
      E1 = (LR * RNQOX / XVR) * EEXP(-A1,IEX)
      R1 = (RNQOX / XVR)
      R1=ALOG(R1)
      W1 = VAQ / XVR
      W2 = VAQ / XVR - LR
      W3 = XRNLDX + VAQ / XVR
      E2 = E1 / W2
      E2 = ALOG(E2)
      W5 = E2 - W3 * TVAQ
      W6 = W2 * TVAQ
      W7 = W2 * TFAIL
      W8 = R1 - A1 + W1 * TFAIL - W3 * TVAQ
      B2=EEXP(B1,IEX)
      A3=EEXP(A1,IEX)
      X1 = XMU(TVAQ,IEX,XVR,XAREA,XK1,XRNLDX)
      X2 = XMU(TT,IEX,XVR,XAREA,XK1,XRNLDX)
      X3 = EEXP(X1 - X2 ,IEX)
      CTVAQ = EEXP(W5 + W6,IEX) - EEXP(W5 + W7,IEX)
      CTVAQ = CTVAQ + EEXP(W8,IEX) * (A3-B2)
      H1 = CTVAQ * X3
      RERR = .095
      AERR = 0.0
      Y = DCADRE(AF2,TVAQ,TT,AERR,RERR,ERROR,IER)
      IF (IER .LT. 100) GO TO 200
  200 CT = Y + H1
      CONVT  = CT
      RETURN
      END
      FUNCTION CONVQ (TT,IEX,VAQ,RNSOL,RNLDX,RNQOX,VR,CLIFE,
     1                 TFAIL,TVAQ,AREA,K1,LR)
C
      REAL LR,K1
C
      AL1 = (VAQ / VR) - LR
      AL2 = RNLDX + VAQ / VR
      AL3 = - LR - RNLDX
      A2 = LR * CLIFE
      A1 = RNQOX / VR
      E1 = A1 * LR / AL1
      G1 = VAQ * TFAIL / VR
      G2 = -LR * CLIFE
      G3 = AL1 * TFAIL - AL2 * TT
      Y1 = E1
      Y2 = EEXP(AL3*TT+A2,IEX) - EEXP(G3+A2,IEX)
      Y3 = A1
      Y4 = 1.- EEXP(-LR * TFAIL+A2,IEX)
      Y5 = EEXP(-AL2 * TT+G1,IEX)
      CT = Y1 * Y2 + Y3 * Y4 * Y5
C
      CONVQ = CT
C
      RETURN
      END
```

```
      FUNCTION CONHYD(TT,IEX,VAQ,RNSOL,RNLDX,RNQOX,VR,CLIFE,
     1                 TFAIL,TVAQ,AREA,K1,LR)
      REAL LR,K1
      A1 = CVC * AREA * K1 / VR
      A4 = VAQ / VR
      IF ( A1 .GT. A4 ) A1 = A4
      A2 = LR * RNQOX * EEXP(LR * CLIFE,IEX) / VR
      A3 = A1 - LR
      TCUT = 10000.
      IF(TVAQ .GE. TCUT) CX = CONVQ(TCUT,IEX,VAQ,RNSOL,RNLDX,RNQOX,
     1                  VR,CLIFE,TFAIL,TVAQ,AREA,K1,LR)
      IF(TVAQ .LT. TCUT) CX = CONVT(TCUT,VAQ,RNSOL,RNLDX,RNQOX,
     1                  VR,CLIFE,TFAIL,TVAQ,AREA,K1,LR)
      X1 = EEXP(-(RNLDX + LR) * TT,IEX)
      X2 = RNLDX + A1
      X3 = - X2 * TT + A3 * TCUT
      X4 = EEXP(X3,IEX)
      X5 = EEXP(X2 * (TCUT - TT),IEX)
      CONHYD = A2 * (X1 - X4) / A3 + CX * X5
      RETURN
      END
      FUNCTION TSOLDR (VR,LR,CLIFE,RNQO,RNLD,FTANK,TB,TI,RNSOL,IEX)
      REAL LR
      TSOL = TB
      FR = FTANK * RNQO
      A = VR * RNSOL
      B = (FR + VR * RNSOL * EEXP(RNLD*CLIFE,IEX))
      C = RNLD * A
      DEL = ( TB - TI ) / 100.
      NN = 100
      DO 4 I = 1,NN
      T = TI + I * DEL
      CA = TANK(VR,LR,CLIFE,T,FR,RNLD,IEX)
      IF ( CA .GE. RNSOL ) GO TO 5
    4 CONTINUE
      GO TO 3
    5 DO 1 I = 1,NN
      T = TI + I * DEL
      ACT = B * EEXP(-RNLD*T,IEX) - A
      FT = C / ACT
      IF ( FT .GE. LR ) TSOL = T
      IF ( FT .GE. LR ) GO TO 2
    1 CONTINUE
    2 TSOLDR = TSOL
      RETURN
    3 TSOLDR = -1
      RETURN
      END
```

Appendix F

INPUT GUIDE FOR REPRISK

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INPUT GUIDE FOR REPOSITORY RISK CODE (REPRISK)

January 21, 1981

Input for this code consists of one job control card, a variable number of alphanumeric title cards, and a variable number of standardized format cards which enter the remainder of the data required for a problem.

With some exceptions, the standardized format cards may be entered in any order; exceptions are indicated in this guide. The job control card must be the first input card, followed by the title cards, and the standardized format cards.

In many cases, the code will assume values or instructions if no quantity is entered for a particular parameter. These default options are also indicated below.

The program dimension statements may be changed (and the program recompiled) to treat problems of different sizes. The amount of allowable input is affected by these dimensions, and the appropriate limiting parameters are indicated in this guide. These parameters are the following, which are clearly indicated in the dimension statements of the program:

NDCTM	Maximum number of dose commitment times
NEVTM	Maximum number of event times
NEVSM	Maximum number of events
NRNM	Maximum number of radionuclides

If requested, the code will write data files to create "complementary cumulative distribution function (ccdf)" plots of the results of a run (see Appendix G). The number of files written by each run is determined by four input variables. These variables are indicated in this input guide by a "plot file" designation (see pages 294, 295, and 298) together with instructions on associating a number with each variable. The product of these four "plot file" numbers determines how many files will be written. Appropriate file-handling control cards must be included for this number of files for the run to be completed.

For further information contact: Dan Egan (703) 557-8610
Office of Radiation Programs (ANR-460)
U. S. Environmental Protection Agency
Washington, DC 20460

JOB CONTROL CARD (Format 16I5) - CONTINUED ON FOLLOWING PAGE

NLINE

Number of title cards to be read (0 to 6)

IREP

Type of repository strata to be considered
1 = salt
2 = non-salt

NSG

Three types of consequence calculations are performed by the code:
Somatic health effects (S)
Genetic health effects (G)
"Release Ratios" (R)
("release ratios" become curies released if no release limits are entered on the radionuclide data cards)

This variable is an index to determine which consequences will be displayed in the detailed output, including ccdf plots. The following table indicates the various combinations ("x"), and also shows appropriate "plot file" numbers for determining the number of ccdf plots

	S	G	R	"plot file" number
1 =	x	–	–	1
2 =	–	x	–	1
3 =	–	–	x	1
4 =	x	x	–	2
5 =	x	–	x	2
6 =	–	x	x	2
7 =	x	x	x	3

Default = 3

NINT

Index for type of input reproduction selected
1 = unformatted "echo" of input cards
2 = descriptive display of input (not yet available)
Default = 2

NMAT

Index to determine printer output format
1 = print summed risks for each problem
2 = print matrix of consequences and probabilities for each event and event time
Default = 2

JOB CONTROL CARD (Format 16I5) - CONTINUED (see previous page)

NPCA	Index to determine whether raw data for pc plots are printed 1 = do not print 2 = print Default = 2	
NPCP	Index to determine whether ccdf plot files are prepared 1 = do not write plot files 2 = write plot files Default = 1	"plot file" no. 0 1
NDOO	Index to determine whether cumulative (O-A, O-B, etc.) and/or incremental (O-A, A-B, etc.) dose commitments are calculated. 1 = cumulative 2 = incremental 3 = both cumulative and incremental Default = 1	"plot file" no. 1 1 2
NN	Indicates the number of time steps used in functions with numerical integration techniques. Must be an even number (recommended between 20 and 50)	
NT	Indicates the time step size used in the functions which calculate the groundwater transit times from the repository to the overlying aquifer. (Recommendation, set to 1)	
IDRILL	Index to determine whether aquifer releases are considered for drilling events which do not hit canister 1 = do not consider 2 = consider Default = 1	

TITLE CARDS (Format 20A4)

Up to six cards may be used for entering title.

First two cards will be used to title all sets of matrix output.

Remaining title cards will only be printed at introduction of problem.

Number of title cards must be indicated on Job Control Card as NLINE.

STANDARDIZED FORMAT CARDS (Format 2I2, 6E10.4,4A4)

These cards enter the remainder of the data for a problem. The first integer field enters the "type" of card to identify the data being provided. Thus, a card with a "10" in first field is a "Type 10" card. This nomenclature will be used in the remainder of this guide.

The fields of this card are designated N1, N2, F(1 through 6), and A(1 through 4). The entries on the following sheets correspond to these designations.

TYPE 10 CARD Dose Integration Time Period

N1		10
N2		-
F(1)	TDINT	End of Dose Integration Time Period (years), which is assumed to start at time = zero. This entry is intended to allow integration of health effects over a longer period that the dose commitment time periods defined on the Type 11 cards. This entry must be larger than any of the dose commitment time periods. Default: If no entry is made, doses are integrated to the end of the dose commitment time period(s) established by the Type 11 cards.

TYPE 11 CARDS	Dose Commitment Time Periods
N1	11
N2	-
F(1 - 6) TEDC(I)	End of Dose commitment time periods (years), which are assumed to start at time = zero or the next smaller dose commitment time period--depending upon the entry for NDOO on the Job Control Card. Up to NDCTM times may be entered to define dose commitment periods for consideration of release events. These times may be entered in any order, since the code will sort them in increasing order.

"plot file" number = the number of dose commitment time period entries

TYPE 20 CARDS	Event Time Periods
N1	20
N2	-
F(1 - 6) TOBND(I)	Event time period outer bounds (years). Up to NEVTM times may be entered to define the outer bound of each event time period--the time period is assumed to start at the next smaller time period "outer bound"--or zero if there is no smaller entry. These time periods are used to calculate the failure probabilities of the events occurring at a particular "event time." Since this card defines the outer bound of each period, they are used as in this example: Entries of 10, 50, and 100 would establish "event times" of 5, 30, and 75 years. The probability of the event occurring at 30 years would be calculated by considering the failure rate over the period 10 to 50 years. And so on...

TYPE 22 CARD Distribution of Atmospheric Releases

N1		22
N2		-
F(1)	FAL	Fraction of atmospheric releases which are distributed through the atmosphere over land
F(2)	FLL	Fraction of direct releases which go directly onto land surfaces
F(3)	FAW	Fraction of direct releases which are distributed through the atmosphere over water (considered for ocean pathway uptake)

TYPE 23 CARDS Event Characterizations (Part 1)

ONE CARD FOR EACH EVENT CONSIDERED - UP TO NEVSM EVENTS

N1		23
N2	NEVTT(I)	Event Type 1 = Atmospheric release (e.g. volcanos) 2 = Land Surface release ("Drilling Hits" canister) 3 = Release from drilling events not hitting canister ("Drilling/No Hit") 4 = Aquifer release from non-drilling events 5 = Aquifer release from normal groundwater flow
F(1)	EVNT(I)	Event Identification Number (taken from ADL report)
F(2)	FHIT(I)	Fraction of repository inventory in canisters directly breached by failure event
F(3)	FTANK(I)	Fraction of repository inventory with which groundwater flow can communicate Default = 1.0 For Type 3 and 4 events only
F(4)	VTANK(I)	Porosity volume of that portion of repository with which groundwater flow can communicate (cubic meters) Default = VR entered on Type 52 card For Type 3 and 4 events only
F(5)	VDRILL(I)	Volume of water removed from repository during a drilling event (cubic meters) Default = VTANK(I) For Type 3 events only
A(1 - 4)	EDES(I,4)	16 character event identification.

TYPE 24 CARDS Event Characterizations (Part 2)

ONE CARD FOR EACH EVENT CONSIDERED - UP TO NEVSM EVENTS

N1		24
N2		-
F(1)	EVNT(I)	Event Identification Number (see Type 23 Card)
F(2)	K1(I)	Initial hydraulic conductivity in flow path created by failure event (meters/year) For Type 3 and 4 events only
F(3)	KPRIM(I)	Rate of change of hydraulic conductivity in flow path created by failure event (meters/year per year) For Type 3 events only
F(4)	PORS(I)	Porosity in flow path created by failure event For Type 3 and 4 events only
F(5)	AREA(I)	Cross-sectional area of flow path created by failure event (square meters)
A(1 - 4)	EDES(I,4)	16 character event identification.

**** NOTE 1: A Type 24 card for an event must appear somewhere AFTER (not necessarily immediately after) the Type 23 card for that event. This is an exception to the general rule that standardized format cards may appear in any order.

TYPE 25 CARDS Event Failure Rate Data

ONE SET OF CARDS FOR EACH EVENT WHICH DOES NOT HAVE A TYPE 26 CARD

N1		25
N2		Sequence number of card (up to six cards in a set)
F(1)	EVNT(I)	Event Identification Number (See Type 23 Card)
F(2 - 6)	FRATE(I)	Failure rate of the event over the event time period (events/year)
A(1 - 4)	EDES(I,4)	16 character event identification.

**** NOTE 1: Failure rates must be entered in order of increasing event time period. This is true regardless of the order in which the event time periods are entered on the Type 20 cards.

**** NOTE 2: Where a failure rate is constant over one or more time periods, it does not have to be entered repeatedly. When the program reads a blank in an FRATE field, it will assign the failure rate from the preceding field. Thus, if the failure rate is constant over the entire time period considered, it only needs to be entered in the first FRATE field. (If it is desired to enter a zero rate after a non-zero rate, providing any negative number will do this.)

**** NOTE 3: For events which are prevented by institutional control for some time after disposal, the procedure described in NOTE 2 may still be used. Although non-zero failure rates may be input for event time periods during institutional control, the program will subsequently set these rates to zero for the period of institutional control (TIC - entered on the Type 52 card).

**** NOTE 4: The set of failure rate cards for an event must appear somewhere AFTER (not necessarily immediately after) the Type 23 card for that event. This is an exception to the general rule that standardized format cards may appear in any order.

TYPE 26 CARDS Initial Event Probability

ONE CARD FOR EACH EVENT WHICH DOES NOT HAVE A SET OF TYPE 25 CARDS

N1		26
N2		-
F(1)	EVNT(I)	Event Identification Number (See Type 23 Card)
F(2)	PROB(I,1)	Initial Probability of Event For events which are assumed to start at repository sealing (essentially design failures). Event is assumed to occur at the midpoint of the first event time period.
A(1 - 4)	EDES(I,4)	16 character event identification.

**** NOTE 1: If both a Type 26 card and a set of Type 25 cards are entered for the same event, the Type 26 card will be used and the Type 25 cards ignored.

**** NOTE 2: The initial probability card for an event must appear somewhere AFTER (not necessarily immediately after) the Type 23 card for that event. This is an exception to the general rule that standardized format cards may appear in any order.

TYPE 30 CARDS Radionuclide Data - Part 1

ONE TYPE 30 CARD FOR EACH RADIONUCLIDE - UP TO NRNM RADIONUCLIDES

N1		30
N2	NRNTY(I)	Radionuclide Type 1 = Simple Decay 2 = Daughter Product
F(1)	RNID(I)	Radionuclide Identification Number (Formed from radionuclide atomic number and mass number. For example, C-14 identification number is 6.014, Pu-239's is 94.239, etc.)
F(2)	0.693/ RNLD(I)	Half-Life (years), which is immediately converted to the decay constant: RNLD(I)
F(3)	RNQO(I)	Initial Inventory at Repository Sealing (curies)
F(4)	LR(I)	Leach rate (fraction per year), if different than the overall waste form leach rate (WFLR - entered on the Type 52 card). If no value entered, WFLR is assumed.
F(5)	RNDA(I)	Retardation Factor in overlying aquifer
F(6)	RNSOL(I)	Solubility Limit on flow through repository (curies/cubic meter)
A(1, 2)	RNDS1(I) RNDS2(I)	Eight character radionuclide identification

TYPE 31 CARDS Radionuclide data - Part 2

ONE TYPE 31 CARD FOR EACH RADIONUCLIDE - UP TO NRNM RADIONUCLIDES

N1		31
N2		-
F(1)	RNID(I)	Radionuclide Identification Number (see Type 30 card)
F(2)	LAMS(I)	Radionuclide-specific rate constant for transfer of radionuclides from available to unavailable soil (per year) Default = GLMS entered on Type 60 card
F(3)	RNKD(I)	Distribution Coefficient in ocean sediments (milliliters/gram)
F(4)	RLMT(1,I)	Release Limit in 40 CFR 191 for air releases (curies)
F(5)	RLMT(2,I)	Release Limit in 40 CFR 191 for land surface releases (curies)
F(6)	RLMT(3,I)	Release Limit in 40 CFR 191 for water releases (curies)
A(1, 2)		Eight character radionuclide identification

**** NOTE 1: If the Release Limits for a radionuclide for all three release modes are the same, only one entry in any one of the three RLMT field needs to be made. The program will assign this limit to all three categories.

**** NOTE 2: If it is desired that the curies released for a radionuclide be calculated, rather than the "Release Ratio", this can be accomplished by leaving all three RLMT fields blank. The program will automatically assign RLMT values of one, and will label the appropriate output "CURIES RELEASED" rather than "RELEASE RATIOS".

**** NOTE 3: The Type 31 card for a radionuclide must appear somewhere AFTER (not necessarily immediately after) the Type 30 card for that radionuclide. This is an exception to the general rule that standardized format cards may appear in any order.

TYPE 32 CARDS Radionuclide data - Part 3

ONE TYPE 32 CARD FOR EACH RADIONUCLIDE WHICH IS A DAUGHTER PRODUCT UP TO NRNM RADIONUCLIDES

N1		32
N2		-
F(1)	RNID(I)	Radionuclide Identification Number (see Type 30 card)
F(2)	0.693/ RNLD1(I)	Half-Life of Parent Radionuclide (years), which is immediately converted to the decay constant: RNLD1(I)
F(3)	RNQ01(I)	Initial Inventory of Parent Radionuclide (curies)
F(2)	0.693/ RNLDX(I)	Artificial Half-Life of Daughter Radionuclide (years), which is immediately converted to the decay constant: RNLDX(I)
F(5)	RNQOX(I)	Artificial Initial Inventory of Daughter Radionuclide (curies)
A(1, 2)		Eight character radionuclide identification

**** NOTE 1: The "artificial" Half-Life and Inventory for daughter radionuclides are for use in the groundwater transport equations. These equations do not treat decay chains, and the time-dependent inventories of daughter products must be approximated as if they were simple-decay radionuclides.

**** NOTE 2: The Type 32 card for a radionuclide must appear somewhere AFTER (not necessarily immediately after) the Type 30 card for that radionuclide. This is an exception to the general rule that standardized format cards may appear in any order.

TYPE 50 CARD Aquifer Flow System Data

N1		50
N2		-
F(1)	XA	Distance along aquifer to "accessible environment" outlet (meters)
F(2)	XS	Distance from top of repository to bottom of overlying aquifer (meters)
F(3)	XKA	Permeability in aquifer pathway (meters/year)
F(4)	XIA	Gradient in aquifer pathway
F(5)	PORA	Effective Porosity in aquifer pathway
F(6)	AQAREA	Cross-sectional area of aquifer overlying the repository (square meters) - (normally the thickness of the aquifer times the widest dimension of the repository floor area)

TYPE 51 CARD　　Hydraulic Gradient Data

N1	51	
N2	-	
****	These parameters mathematically describe an exponential fit of the hydraulic gradients due to the thermal buoyancy effects of repository heat generation and an aquifer interconnection (if any). As many as 10 sets of coefficients may be entered, resulting in a sum of 10 exponentials plus a constant..	
F(1)	ALPH(I)	Hydraulic gradient equals the sum of all "I" CVA(I) * exp[-ALPH(I) * t] terms plus CVC
F(2)	CVA(I)	
F(3)	CVC	

TYPE 52 CARD

Leach Rate, Canister Lifetime, and Other Miscellaneous Data

N1		52
N2		-
F(1)	WFLR	Leach Rate of waste form (fraction per year) NOTE: Different leach rates for specific radionuclides may be entered on the Type 30 cards. If a non-zero value is entered there, it will take precedence over this value.
F(2)	CLIFE	Canister Lifetime (years)
F(3)	VR	Porosity volume of the mined portion of the repository (cubic meters)
F(4)	TIC	Time over which institutional controls are assumed to be effective in preventing intrusion by drilling (years)
F(5)	EXPECT	The expected value for an event over the dose commitment time period which determines whether multiple occurrences of the same event are considered. (Recommended input = 0.5)

TYPE 53 CARD Repository Closure and Flow Data
(Salt Repositories Only)

N1		53
N2		–
F(1)	TCLOS	Time over which salt repository porosity volume decreases from initial volume, VR, to minimum porosity volume, VMIN (years)
F(2)	VMIN	Minimum repository volume (cubic meters)
F(3)	XHGH	Distance from top of overlying aquifer to repository horizon (meters)
F(4)	XLOW	Distance from bottom of overlying aquifer to repository horizon (meters)
F(5)	XILTH	Effective gradient created by pressure of resealing salt on the water in the respository after resaturation.

TYPE 60 CARD Environmental Transfer Factors

N1		60
N2		-
F(1)	GLMS	Rate constant for transfer of radionuclides from available to unavailable soil (per year)
F(2)	LAMR	Rate constant for resuspension of radionuclides from soil to air (per year)
F(3)	LAMG	Rate constant for deposition from air to ground (per year)
F(4)	LAMW	Rate constant for deposition from air to ocean (per year)

TYPE 70 CARD Ocean Environmental Pathway Data

N1		70
N2		-
F(1)	S1IO	Sedimentation coefficient for upper ocean Equals 1.33E-7 (per year) when radionuclide distribution coefficients are in milliliters/gram.
F(2)	S2IO	Sedimentation coefficient for lower ocean Equals 2.55E-9 (per year) when radionuclide distribution coefficients are in milliliters/gram.
F(3)	TAU1	Transfer rate coefficient from upper to lower ocean (per year)
F(4)	TAU2	Transfer rate coefficient from lower to upper ocean (per year)

TYPE 96, 97, 98 or 99 CARDS Data separator cards

**** ONE of these cards must be used at the end of a data set to indicate proper processing for subsequent problems (if any). Subsequent runs will use the data entered for the previous problem, but modified or expanded by the cards entered after the data separator. After the data separator, a new JOB CONTROL CARD must be entered, followed by the appropriate number of TITLE CARDS (the NLINE parameter on the new JOB CONTROL CARD), followed by new standardized format data cards as appropriate.

N1 96 DELETE OLD EVENT(S), CONSIDER NEW EVENT(S)

Indicates end of data for a particular problem. Tells program that another problem will follow.
The next problem will neglect all event data entered previously, and will only address event data entered after this separator.

N1 97 DELETE OLD RADIONUCLIDE(S), CONSIDER NEW RADIONUCLIDE(S)

Indicates end of data for a particular problem. Tells program that another problem will follow.
The next problem will neglect all radionuclide data entered previously, and will only address radionuclide data entered after this separator.

N1 98 MODIFY OTHER DATA

Indicates end of data for a particular problem. Tells program that another problem will follow.
Data entered on following cards will modify previous data. ALL VALUES ON A NEW CARD MUST BE ENTERED, EVEN IF ONLY A FEW ARE BEING CHANGED. If cards for a new event or a new radionuclide are entered after this type of a separator, this new event or radionuclide will be ADDED to those considered previously.

N1 99 END OF RUN

Indicates end of data for all problems.
Tells program that no additional problems will follow.

Appendix G

SAMPLE INPUT AND OUTPUT FOR REPRISK

Table G-1: REPRISK Input Cards for Sample Problem

```
    3    1    1    1    0    1    2    1   50    1    1
  PROGRAM = REPRISK   JCL = IMSL.REPRISK   REPOSITORY = SALT
  DATASET = SALT.BASECASE           DATE 04/18/81
  THIS IS A RUN USING ADL'S FIRST ESTIMATES.
11      10000.
20        100.      500.     1000.     2000.     5000.    10000.
22         .15       .50       .35
23 1      74.0    1.0E-3                                           METEORITE
25 1      74.0   4.0E-11                                           METEORITE
23 1      73.0    4.0E-3                                            VOLCANO
25 1      73.0   1.0E-10                                            VOLCANO
23 2      40.1    4.0E-6                                           DRILLING/HIT
25 1      40.1    2.0E-5                                           DRILLING/HIT
23 4      71.0    3.0E-3       .05     1.E+5                        FAULTING
24        71.0     31.50       0.0       0.1    4000.0              FAULTING
25 1      71.0    2.0E-8                                            FAULTING
23 4      75.0    4.0E-3      .016    3.2E+4                        BRECCIA
24        75.0    3150.0       0.0        .2   30000.0              BRECCIA
25 1      75.0                        1.0E-8                        BRECCIA
23 3      40.2               6.E-5       .06                     DRILLING/NO HIT
24        40.2   3.15E-3   3.15E-4       0.1       0.5           DRILLING/NO HIT
25 1      40.2    2.0E-2                                         DRILLING/NO HIT
23 5      11.0                                                   ROUTINE RELEASE
24        11.0   3.40E-3   5.00E-5       0.1     500.0           ROUTINE RELEASE
26        11.0       1.0                                         ROUTINE RELEASE
30 1    94.238       89.     2.2E8                100.    1.7E-2 PU-238
31      94.238     5.E-4    2.0E+3    4.0E+4                     PU-238
30 2    94.239    24400.     3.3E7                100.     6.E-5 PU-239
31      94.239     5.E-4     2.E+3    1.0E+4                     PU-239
32      94.239     7950.     1.7E6                               PU-239
30 1    94.240     6760.     4.9E7                100.    2.2E-4 PU-240
31      94.240     5.E-4     2.E+3    1.0E+4                     PU-240
30 1    94.242    3.79E5     1.7E5                100.     4.E-6 PU-242
31      94.242     5.E-4    2.0E+3    1.0E+4                     PU-242
30 2    95.241      458.     1.7E8                100.     160.0 AM-241
31      95.241     5.E-4     1.E+3    1.0E+3                     AM-241
32      95.241      13.2     8.0E9      567.     3.9E8           AM-241
30 1    95.243     7650.     1.7E6                100.      10.0 AM-243
31      95.243     5.E-4     1.E+3    4.0E+2                     AM-243
30 2    93.237    2.14E6     3.3E4                100.     7.E-7 NP-237
31      93.237     5.E-2        1.    2.0E+3                     NP-237
32      93.237    4.58E2     1.7E8               1.0E5           NP-237
30 1    55.135      3.E6     2.2E4                  1.       0.0 CS-135
31      55.135    2.1E-3    2.0E+1    2.0E+5                     CS-135
30 1    55.137       30.     8.6E9                  1.       0.0 CS-137
31      55.137    2.1E-3    2.0E+1    5.0E+4                     CS-137
```

Preceding page blank

Table G-1 (continued): REPRISK Input Cards for Sample Problem

```
30 1     53.129     1.6E7     3.8E3                   1.       0.0 I -129
31       53.129    1.2E-1       0.0    9.0E+4                      I -129
30 1     43.099     2.1E5     1.4E6                   1.     2.E-5 TC- 99
31       43.099     1.260       0.0    2.0E+5                      TC- 99
30 1     50.126      1.E5     5.6E4                  10.    3.0E-2 SN-126
31       50.126    4.5E-3       0.0    8.0E+3                      SN-126
30 1     40.093     9.5E5     1.9E5                 100.    2.6E-6 ZR- 93
31       40.093    5.0E-4    2.0E+3    1.0E+4                      ZR- 93
30 1     38.090      28.8    6.0E+9                   1.       0.0 SR- 90
31       38.090    9.5E-3    2.0E+0    8.0E+3                      SR- 90
30 1      6.014     5730.     2.8E4                   1.       0.0 C - 14
31        6.014       0.5       0.0    2.0E+4                      C - 14
50       1600.0     200.0      31.5      0.01       0.15     1.2E5
51       1.6E-3      .132       0.1
51       3.1E-4      .103
51       2.6E-4      .283
52       1.0E-4     100.0     2.0E6     100.0        0.5
53       2.0E+2    2.0E+4    1.3E+2    1.0E+2        7.9
60       5.0E-4   3.16E-4      24.4      48.7
70      1.33E-7    2.5E-9   3.10E-2   6.25E-4
99
```

Table G-2: REPRISK Output for Sample Problem

```
--------------------------------------------------------------------------------------------------------------------------

                         PROGRAM = REPRISK   JCL = IMSL.REPRISK   REPOSITORY = SALT
                         DATASET = SALT.BASECASE             DATE 04/18/81

--------------------------------------------------------------------------------------------------------------------------
*****   THE (P)(C) RISK FOR THIS DOSE COMMITMENT PERIOD IS 1.86E+02 FOR SOMATIC EFFECTS, AND 2.45E+00 FOR GENETIC EFFECTS   *****
--------------------------------------------------------------------------------------------------------------------------
*****   THE (P)(C) RISK BY EVENT IS:                                                                                       *****
*****                    EVENT  74.0      METEORITE       3.40E-03 FOR SOMATIC EFFECTS     3.01E-05 FOR GENETIC EFFECTS    *****
*****                    EVENT  73.0       VOLCANO        3.40E-02 FOR SOMATIC EFFECTS     3.01E-04 FOR GENETIC EFFECTS    *****
*****                    EVENT  40.1    DRILLING/HIT      4.52E+00 FOR SOMATIC EFFECTS     3.51E-02 FOR GENETIC EFFECTS    *****
*****                    EVENT  71.0      FAULTING        6.85E-03 FOR SOMATIC EFFECTS     4.50E-04 FOR GENETIC EFFECTS    *****
*****                    EVENT  75.0       BRECCIA        9.59E-04 FOR SOMATIC EFFECTS     6.04E-05 FOR GENETIC EFFECTS    *****
*****                    EVENT  40.2  DRILLING/NO HIT     1.81E+02 FOR SOMATIC EFFECTS     2.41E+00 FOR GENETIC EFFECTS    *****
*****                    EVENT  11.0  ROUTINE RELEASE     0.0      FOR SOMATIC EFFECTS     0.0      FOR GENETIC EFFECTS    *****
--------------------------------------------------------------------------------------------------------------------------
*****   THE (P)(C) RISK BY RADIONUCLIDE IS:                                                                                *****
*****                                     PU-238      2.54E-03 FOR SOMATIC EFFECTS     5.05E-06 FOR GENETIC EFFECTS    *****
*****                                     PU-239      1.08E+00 FOR SOMATIC EFFECTS     3.01E-03 FOR GENETIC EFFECTS    *****
*****                                     PU-240      1.06E+00 FOR SOMATIC EFFECTS     3.79E-03 FOR GENETIC EFFECTS    *****
*****                                     PU-242      6.28E-03 FOR SOMATIC EFFECTS     2.28E-05 FOR GENETIC EFFECTS    *****
*****                                     AM-241      7.93E+01 FOR SOMATIC EFFECTS     6.07E-01 FOR GENETIC EFFECTS    *****
*****                                     AM-243      1.04E+02 FOR SOMATIC EFFECTS     1.82E+00 FOR GENETIC EFFECTS    *****
*****                                     NP-237      1.90E-04 FOR SOMATIC EFFECTS     8.08E-07 FOR GENETIC EFFECTS    *****
*****                                     CS-135      3.63E-02 FOR SOMATIC EFFECTS     6.42E-03 FOR GENETIC EFFECTS    *****
*****                                     CS-137      9.76E-02 FOR SOMATIC EFFECTS     8.64E-03 FOR GENETIC EFFECTS    *****
*****                                     I -129      6.54E-04 FOR SOMATIC EFFECTS     3.51E-06 FOR GENETIC EFFECTS    *****
*****                                     TC- 99      3.13E-04 FOR SOMATIC EFFECTS     1.65E-05 FOR GENETIC EFFECTS    *****
*****                                     SN-126      1.87E-02 FOR SOMATIC EFFECTS     1.80E-03 FOR GENETIC EFFECTS    *****
*****                                     ZR- 93      1.89E-02 FOR SOMATIC EFFECTS     1.88E-03 FOR GENETIC EFFECTS    *****
*****                                     SR- 90      9.86E-02 FOR SOMATIC EFFECTS     2.94E-04 FOR GENETIC EFFECTS    *****
*****                                     C - 14      5.36E-03 FOR SOMATIC EFFECTS     2.12E-04 FOR GENETIC EFFECTS    *****
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Table G-2 (continued): REPRISK Output for Sample Problem

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EACH ENTRY IN THE FOLLOWING TABLES REPRESENTS THE FOLLOWING DATA:

     1.  THE TOTAL NUMBER OF HEALTH EFFECTS FROM ONE SUCH EVENT INCURRED IN THIS DOSE COMMITMENT PERIOD.
     2.  THE RADIONUCLIDE CONTRIBUTING THE MOST HEALTH EFFECTS WITHIN THIS TOTAL.
     3.  THE PROBABILITY OF AT LEAST ONE EVENT OF THIS TYPE OCCURRING WITHIN THE TIME PERIOD REPRESENTED BY THIS EVENT TIME

-----------------------------------------------------------------------------------------------------------------

  DOSE COMMITMENT PERIOD =      0 YEARS TO   10000 YEARS                                    SOMATIC HEALTH EFFECTS

                                                        EVENT TIMES

                         50 YEARS        300 YEARS        750 YEARS       1500 YEARS       3500 YEARS       7500 YEARS

               **************************************************************************************************
               *
      EVENT    *        1.13E+05         4.74E+04         2.65E+04         1.20E+04         4.90E+03         2.93E+03
      74.0     *         AM-241           AM-241           AM-241           AM-241           PU-240           PU-239
    METEORITE  *        4.00E-09         1.60E-08         2.00E-08         4.00E-08         1.20E-07         2.00E-07
               *
      EVENT    *        4.54E+05         1.89E+05         1.06E+05         4.82E+04         1.96E+04         1.17E+04
      73.0     *         AM-241           AM-241           AM-241           AM-241           PU-240           PU-239
     VOLCANO   *        1.00E-08         4.00E-08         5.00E-08         1.00E-07         3.00E-07         5.00E-07
               *
      EVENT    *        1.69E+02         1.17E+02         6.99E+01         3.67E+01         1.91E+01         1.10E+01
      40.1     *         AM-241           AM-241           AM-241           AM-241           PU-240           PU-239
  DRILLING/HIT *        0.0              8.00E-03         1.00E-02         2.00E-02         5.82E-02         9.52E-02
               *
      EVENT    *        9.35E+01         9.30E+01         9.19E+01         8.98E+01         2.45E+01         1.73E+01
      71.0     *         SN-126           SN-126           SN-126           SN-126           C - 14           C - 14
     FAULTING  *        2.00E-06         8.00E-06         1.00E-05         2.00E-05         6.00E-05         1.00E-04
               *
      EVENT    *        3.23E+01         3.16E+01         3.03E+01         2.81E+01         8.83E+00         5.22E+00
      75.0     *         SN-126           SN-126           SN-126           SN-126           C - 14           C - 14
     BRECCIA   *        0.0              0.0              5.00E-06         1.00E-05         3.00E-05         5.00E-05
               *
      EVENT    *        0.0              0.0              0.0              0.0              0.0              0.0
      11.0     *
ROUTINE RELEASE *       1.00E+00         0.0              0.0              0.0              0.0              0.0
               *
-----------------------------------------------------------------------------------------------------------------
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Table G-2 (continued): REPRISK Output for Sample Problem

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FOR RELATIVELY LIKELY HUMAN INTRUSION EVENTS, MULTIPLE OCCURRENCES ARE ASSUMED.  THE EVENT TIMES FOR EACH OCCURRENCE ARE EVENLY
SPACED THROUGHOUT THE PERIOD FROM LOSS OF INSTITUTIONAL CONTROLS (  100 YEARS) TO THE END OF THE EVENT PERIOD ( 10000 YEARS).
FOR EACH CASE, THE CONSEQUENCES ARE SUMMED OVER THESE MULTIPLE OCCURRENCES.

------------------------------------------------------------------------------------------------------------------------

    EVENT              12 CASES WERE RUN FOR DIFFERENT EXPECTED NUMBERS OF OCCURRENCES.
    40.2               FROM   100 YEARS
DRILLING/NO HIT        TO   10000 YEARS

                   NUMBER OF             PROBABILITY OF            SOMATIC               GENETIC
                  OCCURRENCES             THIS NUMBER          HEALTH EFFECTS        HEALTH EFFECTS

                      159                  5.00E-03               1.45E+02              1.94E+00
                      166                  1.65E-02               1.52E+02              2.02E+00
                      173                  5.00E-02               1.58E+02              2.11E+00
                      180                  9.00E-02               1.65E+02              2.19E+00
                      187                  1.50E-01               1.71E+02              2.28E+00
                      194                  1.90E-01               1.77E+02              2.36E+00
                      201                  1.90E-01               1.84E+02              2.45E+00
                      208                  1.50E-01               1.90E+02              2.53E+00
                      215                  9.00E-02               1.97E+02              2.62E+00
                      222                  5.00E-02               2.03E+02              2.71E+00
                      229                  1.65E-02               2.09E+02              2.79E+00
                      236                  5.00E-03               2.16E+02              2.88E+00

------------------------------------------------------------------------------------------------------------------------

        PROBLEM COMPLETED
```
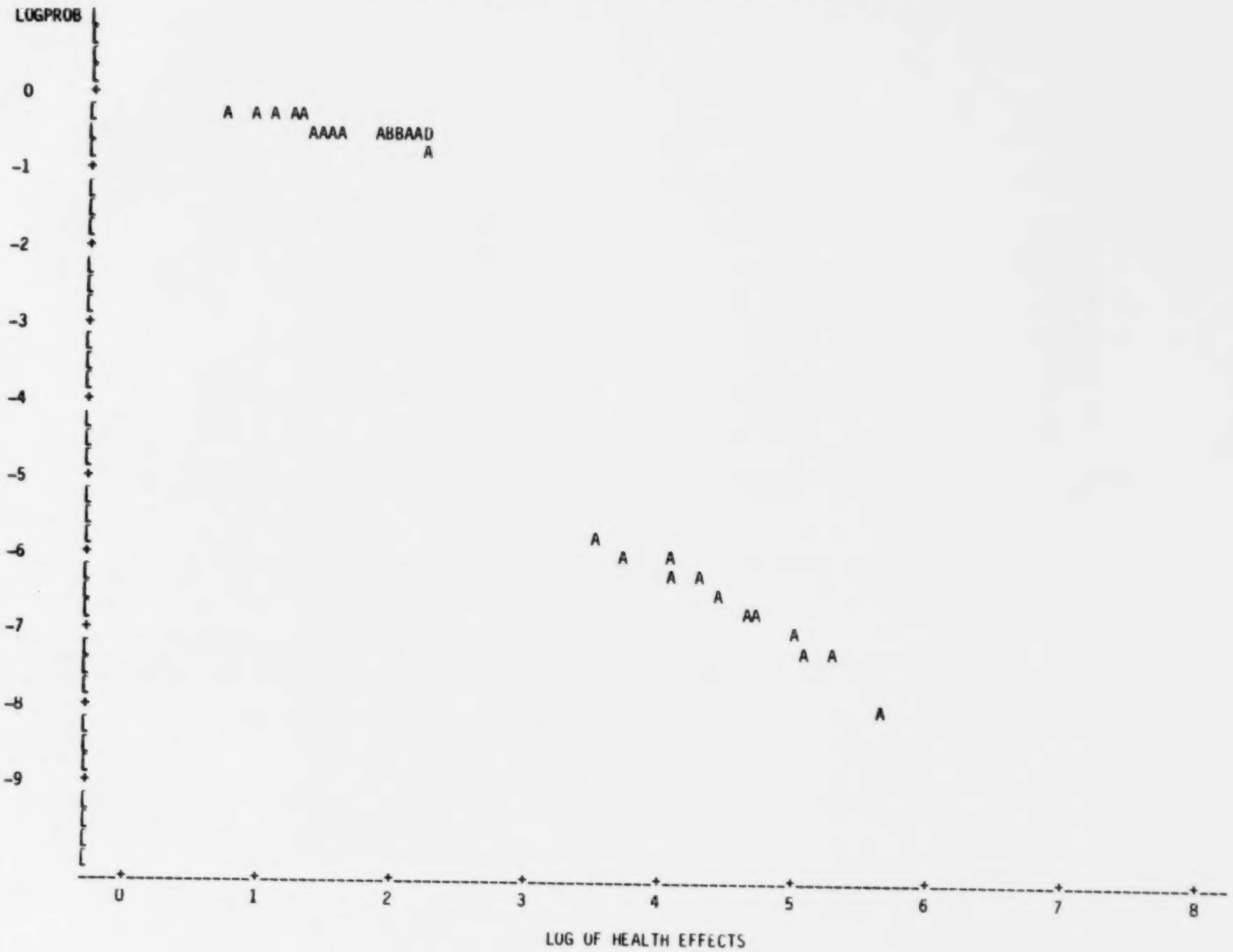

Table G-2 (continued): REPRISK Output for Sample Problem

```
SOMATIC HEALTH EFFECTS FROM ALL EVENTS          ------------- DOSE COMMITMENT TIME OF 0-10000YRS.          1
                                                                          9:36 TUESDAY, JUNE 9, 1981

                         PLOT OF LOGPROB*LOGCON    LEGEND: A = 1 OBS, B = 2 OBS, ETC.
```



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*U.S. GOVERNMENT PRINTING OFFICE : 1983 0-381-085/4498